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CONTENTS.

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STRUTS AND TIE-RODS IN MOTION.

By H. MAWSON, B.Sc., of the University of Liverpool.

[*Selected for Publication only.*]

In the present Paper it is proposed to show how the stresses in a rod which is in motion and subjected to an endlong force may be calculated; and also to show that the formulæ which have been derived for stresses in stationary struts are only special cases of those obtained for rods in motion.

Take first the case of a uniform circular shaft of weight w per unit length rotating at a radians per second in bearings which do not constrain it in any way, and also let it be subjected to an endlong compressive force F.

The rod will be slightly deflected, Fig. 1 (page 462), and in consequence of this deflection y at a distance x from an axis taken through O the centre of the rod, there will be an additional load at this point of $\frac{wa^2y}{g}$ per unit length.

Treating the rod as a strut with only an endlong force F applied to it, we have $\frac{d^2y}{dx^2} = -\frac{\text{F}y}{\text{EI}}$. As a beam $\frac{d^2y}{dx^2} = \frac{\text{M}}{\text{EI}}$.

As a strut laterally loaded or as a combination of strut and beam

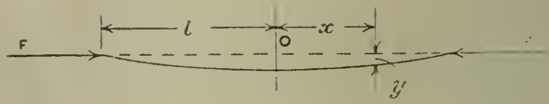
$$\frac{d^2y}{dx^2}=\frac{\mathrm{M}}{\mathrm{EI}}-\frac{\mathrm{F}y}{\mathrm{EI}}$$

$$\frac{d^3y}{dx^3}=\frac{\mathrm{S}}{\mathrm{EI}}-\frac{\mathrm{F}}{\mathrm{EI}}\frac{dy}{dx}$$ where S is the shearing force

$$\frac{d^4y}{dx^4}=\frac{w_1}{\mathrm{EI}}-\frac{\mathrm{F}}{\mathrm{EI}}\frac{d^2y}{dx^2},$$

w_1, denoting the loading per unit length.

Fig. 1.



Taking the worst case when the centrifugal force and weight act together

$$w_1 = w + \frac{w}{g}\,\alpha^2 y,$$

$$\frac{d^4y}{dx^4}+\frac{\mathrm{F}}{\mathrm{EI}}\frac{d^2y}{dx^2}-\frac{w}{g}\frac{\alpha^2 y}{\mathrm{EI}}=\frac{w}{\mathrm{EI}} \quad . \quad . \quad . \quad (1)$$

The solution of this equation is given by

$$y = \mathrm{A}_1 \cos\phi x + \mathrm{A}_2 \sin\phi x + \mathrm{A}_3 e^{\theta x} + \mathrm{A}_4 e^{-\theta x} - \frac{g}{\alpha^2} \quad . \quad (2)$$

where

$$\phi^2 = \frac{\mathrm{F}}{2\mathrm{EI}}+\sqrt{\frac{\mathrm{F}^2}{4\mathrm{E}^2\mathrm{I}^2}+\frac{w\alpha^2}{g\mathrm{EI}}}.$$

and

$$\theta^2 = -\frac{\mathrm{F}}{2\mathrm{EI}}+\sqrt{\frac{\mathrm{F}^2}{4\mathrm{E}^2\mathrm{I}^2}+\frac{w\alpha^2}{g\mathrm{EI}}}.$$

The constants A_1, A_2, A_3 and A_4 can be calculated from the conditions that y has the same values for equal positive and negative values of x, and also when $x = l$ both y and $\frac{d^2y}{dx^2}$ become zero.

From these conditions it will be found that

$$A_1 = 0, \quad A_2 = \frac{\theta^2 g}{a^2 (\theta^2 + \phi^2) \cos \phi l},$$

$$A_3 = A_4 = \frac{\phi^2 g}{2a^2 (\theta^2 + \phi^2) \cosh \theta l}.$$

Placing these values in equation (2), a relation for y is obtained, and remembering that the B.M. $= \mathrm{EI} \frac{d^2 y}{dx^2}$, the B.M. at any point can be found. The B.M. is a maximum when $x =$ zero, and will be found to be

$$M_{\max} = \frac{\mathrm{EI}\theta^2\phi^2 g}{a^2 (\theta^2 + \phi^2)} \left(\frac{1}{\cosh \theta l} - \frac{1}{\cos \phi l}\right)$$

$$= \frac{w}{2\sqrt{\frac{\mathrm{F}^2}{4\mathrm{E}^2\mathrm{I}^2} + \frac{wa^2}{g\mathrm{EI}}}} \left\{\frac{1}{\cosh \theta l} - \frac{1}{\cos \phi l}\right\} \quad . \quad . \quad (3)$$

The maximum stress in the material is given by

$$f_{\max} = \frac{w}{2\mathrm{Z}\sqrt{\frac{\mathrm{F}^2}{4\mathrm{E}^2\mathrm{I}^2} + \frac{wa^2}{g\mathrm{EI}}}} \left\{\frac{1}{\cosh \theta l} - \frac{1}{\cos \phi l}\right\} + \frac{\mathrm{F}}{\mathrm{A}} \quad . \quad (4)$$

A being the sectional area of the shaft, and Z the modulus of section.

Both the stress in the material and the B.M. become infinite when $\cos \phi l = 0$, i.e., when

$$\sqrt{\frac{\mathrm{F}}{2\mathrm{EI}} + \sqrt{\frac{\mathrm{F}^2}{4\mathrm{E}^2\mathrm{I}^2} + \frac{wa^2}{g\mathrm{EI}}}} = \frac{\pi}{2l},$$

$$\mathrm{F} = \frac{\pi^2 \mathrm{EI}}{4l^2} - \frac{4wa^2 l^2}{g\pi^2} \quad . \quad . \quad . \quad . \quad (5)$$

$$\text{or} \qquad a = \frac{\pi}{2l}\sqrt{\frac{g}{w}\left(\frac{\pi^2 \mathrm{EI}}{4l^2} - \mathrm{F}\right)}. \quad . \quad . \quad (6)$$

Equation (5) shows that as a increases, the critical endlong force rapidly diminishes. If also in equation (5) a be put zero, we have a stationary strut loaded with w per unit length, and the critical endlong force is found to be Euler's Load. Again, if a be placed equal to zero, $\phi = \sqrt{\frac{\mathrm{F}}{\mathrm{EI}}}$ and $\theta =$ zero and the maximum stress in equation (4) reduces to

$$f_{max} = \frac{w\mathrm{EI}}{\mathrm{FZ}}\left[1 - \sec l\sqrt{\frac{\mathrm{F}}{\mathrm{EI}}}\right] + \frac{\mathrm{F}}{\mathrm{A}} \quad . \quad . \quad (7)$$

which agrees with that obtained for a stationary strut laterally loaded.*

Equation (6) gives an expression for the critical speed of the shaft which is found to decrease as F increases; moreover, when F is zero, we have an expression for the whirling speed of a shaft rotating in bearings and not subjected to any endlong force.

As a second example, take the case of a rotating shaft subjected to an endlong tensile force F. Treating in exactly the same manner as before, we arrive at the equation

$$\frac{d^4y}{dx^4} - \frac{\mathrm{F}}{\mathrm{EI}}\frac{d^2y}{dx^2} - \frac{wa^2}{g\mathrm{EI}} = \frac{w}{\mathrm{EI}} \quad . \quad . \quad . \quad (8)$$

The solution of this equation is given by

$$y = \mathrm{A}_1 \cos \theta x + \mathrm{A}_2 \sin \theta x + \mathrm{A}_3 e^{\phi x} + \mathrm{A}_4 e^{-\phi x} - \frac{g}{a^2}$$

where θ and ϕ have the same values as before. The same conditions hold as in the first place, and hence

$$\mathrm{A}_1 = 0, \quad \mathrm{A}_2 = \frac{\phi^2 g}{a^2(\theta^2 + \phi^2)\cos\theta l},$$

$$\mathrm{A}_3 = \mathrm{A}_4 = \frac{\theta^2 g}{2a^2(\theta^2 + \phi^2)\cosh\phi l}.$$

The maximum B.M. will be given by

$$\mathrm{M}_{max} = \frac{\mathrm{EI}\theta^2\phi^2 g}{a^2(\theta^2 + \phi^2)}\left\{\frac{1}{\cosh\phi l} - \frac{1}{\cos\theta l}\right\}$$

$$= \frac{w}{2\sqrt{\frac{\mathrm{F}^2}{4\mathrm{E}^2\mathrm{I}^2} + \frac{wa^2}{g\mathrm{EI}}}}\left\{\frac{1}{\cosh\phi l} - \frac{1}{\cos\theta l}\right\} \quad . \quad . \quad (9)$$

$$f_{max} = \frac{w}{2\mathrm{Z}\sqrt{\frac{\mathrm{F}^2}{4\mathrm{E}^2\mathrm{I}^2} + \frac{wa^2}{g\mathrm{EI}}}}\left\{\frac{1}{\cosh\phi l} - \frac{1}{\cos\theta l}\right\} + \frac{\mathrm{F}}{\mathrm{A}} \quad . \quad (10)$$

The B.M. and the stress are now infinite when $\cos\theta l$ is zero, that is, when

* *See* Morley's "Strength of Materials."

$$\sqrt{-\frac{F}{2EI}+\sqrt{\frac{F^2}{4E^2I^2}+\frac{w\alpha^2}{gEI}}}=\frac{\pi}{2l}$$

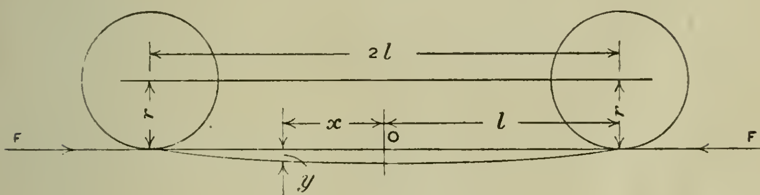
$$F=\frac{4w\alpha^2l^2}{g\pi^2}-\frac{\pi^2EI}{4l^2} \quad . \quad . \quad . \quad . \quad (11)$$

or

$$\alpha=\frac{\pi}{2l}\sqrt{\frac{g}{w}\left(\frac{\pi^2EI}{4l^2}+F\right)} \quad . \quad . \quad (12)$$

Equation (11) agrees exactly with equation (5), for F in this case is $-F$ of the previous case, $F=0$ and $\alpha=0$ give the same relations in equation (11) as they do in (5).

Fig. 2.



From (12), however, the greater the value of F the greater the angular velocity has to be before whirling takes place, and hence whirling might be prevented by applying an endlong tensile force to the rotating shaft.

Placing $\alpha=0$, ϕ becomes $\sqrt{\frac{F}{EI}}$ and θ becomes zero as before, and the maximum stress in equation (10) is given by

$$f_{\max}=\frac{wEI}{FZ}\left\{\operatorname{sech} l\sqrt{\frac{\ }{EI}}-1\right\}+\frac{F}{A},$$

which agrees with the maximum stress for a stationary tie loaded with w per unit length.*

Now consider a uniform rod, every portion of which describes a vertical circle of radius r, Fig. 2, to be subjected to an endlong compressive force F.

Taking the rod in its extreme vertical positions, the equation can again be written

$$\frac{d^4y}{dx^4}=\frac{\text{load per unit length}}{EI}-\frac{F}{EI}\frac{d^2y}{dx^2}.$$

* *See* Morley's "Strength of Materials."

Three cases may arise :—

(a) In which the rod is in its lowest position and the weight and centrifugal force act together. Then the load per unit length at any point distant x from the axis is given by

$$\frac{w}{g}\alpha^2(r+y)+w.$$

(b) The rod in its highest position, the weight and centrifugal force opposing each other, the centrifugal force being the greater, then

$$\text{Load per unit length} = \frac{w}{g}\alpha^2(r+y)-w.$$

(c) Same as case (b), only the weight the greater.

$$\text{Load per unit length} = w-\frac{w}{g}\alpha^2(r+y).$$

Taking case (a) we have

$$\frac{d^4y}{dx^4}+\frac{F}{EI}\frac{d^2y}{dx^2}-\frac{w\alpha^2}{gEI}y=\frac{w+\frac{w}{g}\alpha^2r}{EI} \quad . \quad . \quad (13)$$

an equation only differing from (1) in the constant term on the right-hand side.

The solution of this equation is

$$y = A_1\cos\phi x + A_2\sin\phi x + A_3e^{\theta x} + A_4e^{-\theta x} - \frac{g}{\alpha^2} - r \quad . \quad (14)$$

where θ and ϕ have the same meaning as before.

The same conditions to determine A_1, A_2, A_3, and A_4 may be applied, and the maximum B.M. is now given by

$$M_{max} = \frac{EI\left(\frac{g}{\alpha^2}+r\right)\theta^2\phi^2}{\theta^2+\phi^2}\left\{\frac{1}{\cosh\theta l}-\frac{1}{\cos\phi l}\right\}$$

$$= \frac{w+\frac{w}{g}\alpha^2r}{2\sqrt{\frac{F^2}{4E^2I^2}+\frac{w\alpha^2}{gEI}}}\left\{\frac{1}{\cosh\theta l}-\frac{1}{\cos\phi l}\right\} \quad . \quad (15)$$

$$f_{max} = \frac{w+\frac{w}{g}\alpha^2r}{2Z\sqrt{\frac{F^2}{4E^2I^2}+\frac{w\alpha^2}{gEI}}}\left\{\frac{1}{\cosh\theta l}-\frac{1}{\cos\phi l}\right\}+\frac{F}{A} \quad (16)$$

This again becomes infinite when $\cos \phi l$ is zero. Hence we obtain relations for F and a as given by equations (5) and (6), and the deductions from (5) and (6) apply here also. We have therefore a proof of an interesting fact that a circular rod rotated as a coupling-rod, and subjected to an endlong compressive force, will whirl at the same angular velocity as it would do if rotated as a shaft and subjected to the same endlong force, no matter what the radius r may be, since the moment of inertia about all axes of bending is constant.

Again, if in equation (16) a be made zero, equation (7) is obtained for the maximum stress in a stationary strut carrying a uniformly distributed load of w per unit length.

Treating a tie-rod having the motion of a coupling-rod in a similar manner, we have, corresponding to case (a), the equation

$$\frac{d^4y}{dx^4} - \frac{F}{EI}\frac{d^2y}{dx^2} - \frac{wa^2y}{gEI} = \frac{w + \frac{w}{g}a^2r}{EI} \quad . \quad . \quad (17)$$

The solution of which is given by

$$y = A_1 \cos \theta x + A_2 \sin \theta x + A_3 e^{\phi x} \times A_4 e^{-\phi x} - \frac{g}{a^2} - r$$

$$M_{max} = \frac{EI\left(\frac{g}{a^2} + r\right)\theta^2\phi^2}{(\theta^2 + \phi^2)}\left\{\frac{1}{\cosh \phi l} - \frac{1}{\cos \theta l}\right\}$$

$$= \frac{w + \frac{w}{g}a^2r}{2\sqrt{\frac{F^2}{4E^2I^2} + \frac{wa^2}{gEI}}}\left\{\frac{1}{\cosh \phi l} - \frac{1}{\cos \theta l}\right\} \quad . \quad . \quad (18)$$

$$f_{max} = \frac{w + \frac{w}{g}a^2r}{2Z\sqrt{\frac{F^2}{4E^2I^2} + \frac{wa^2}{gEI}}}\left\{\frac{1}{\cosh \phi l} - \frac{1}{\cos \theta l}\right\} + \frac{F}{A} \quad . \quad (19)$$

The B.M. and stress are again infinite when $\cos \theta l$ is zero, and therefore the values of F and a as given by equations (11) and (12) apply here also. The value $a = 0$ in equation (19) gives the maximum stress in a stationary tie laterally loaded.

Equation (16) has been applied to a particular coupling-rod, which broke whilst in service, and the results are tabulated in Table 1.

TABLE 1.

Speed of Engine in miles per hour.	Steam-Pressure. 160 lb. per sq. in. Stress in rod. Tons per sq. in.	Steam-Pressure. 200 lb. per sq. in. Stress in rod. Tons per sq. in.
10	3·2	3·95
20	3·78	4·60
30	4·70	5·25
40	6·18	6·8
50	7·70	8·7
60	9·82	10·8
70	12·30	13·3
80	15·2	16·4

The particulars and dimensions relating to this rod, which was of I section, were kindly supplied by Mr. George Hughes, Chief Mechanical Engineer to the Lancashire and Yorkshire Railway Co., and are as follows:—

Diameter of cylinder, 18 inches; working steam-pressure, 160 lb. per sq. in.; radius at which rod acts, 12 inches; distance between centres, 8 ft. 11 in.; diameter of wheels to which rod was attached, 6 feet; mean sectional area 6·53 sq. in.; mean moment of inertia I, about the axes of bending, 12·5 in.^{4} units; mean weight per inch run, 1·85 lb. Calculations have been made for steam-pressures of 160 and 200 lb. per square inch at different speeds of the engine, the direct stress $\frac{F}{A}$ being taken as the full steam-pressure on the piston divided by the sectional area of the coupling-rod.

It will be noticed that the stress increases very rapidly as the speed of the engine increases, and that at the high speeds an

increase in steam-pressure does not appear to have as disastrous an effect as an increase in speed. It is also seen that at 60 miles per hour, with the ordinary working pressure of 160 lb. per square inch, the stress in the rod is 9·82 tons per square inch, which is rather high considering that the stresses are of an alternating character, first compressive, and then tensile. Should the wheels slip upon the rail, it is quite possible that they may revolve at a speed equivalent to 80 or more miles per hour, and the stresses may then exceed the elastic limit. Rods have been known to break in cases of derailment owing to the high speed with which they rotate in such cases.

Professor Perry, by considering a coupling-rod to be uniformly loaded and to be bent in a cosine curve, deduced the equation

$$\frac{d^2y}{dx^2} + \frac{\text{F}}{\text{EI}}y + \frac{w_1 l^2}{2\text{EI}}\cos\frac{\pi}{2l}x = 0$$

from which he obtained the stress

$$f_{\max} = \frac{w_1 l^2}{2\text{Z}}\left(\frac{\frac{\pi^2\text{EI}}{4l^2}}{\frac{\pi^2\text{EI}}{4l^2} - \text{F}}\right) + \frac{\text{F}}{\text{A}}.$$

The results obtained by applying his formula to this particular rod are shown in column 7, Table 2 (page 471), and Fig. 3 (page 470), and are found to agree very closely with the more mathematical determination obtained from equation (16) and tabulated in column 9 of the same Table.

Professor Unwin in his work on "Machine Design" gives the formula

$$f = \frac{wv^2l^2}{gr8\text{Z}} \text{ lb. per square inch.}$$

where w is the weight per inch run in pounds,

v the linear velocity of the rod in feet per second,

g the acceleration of gravity in feet per second, per second,

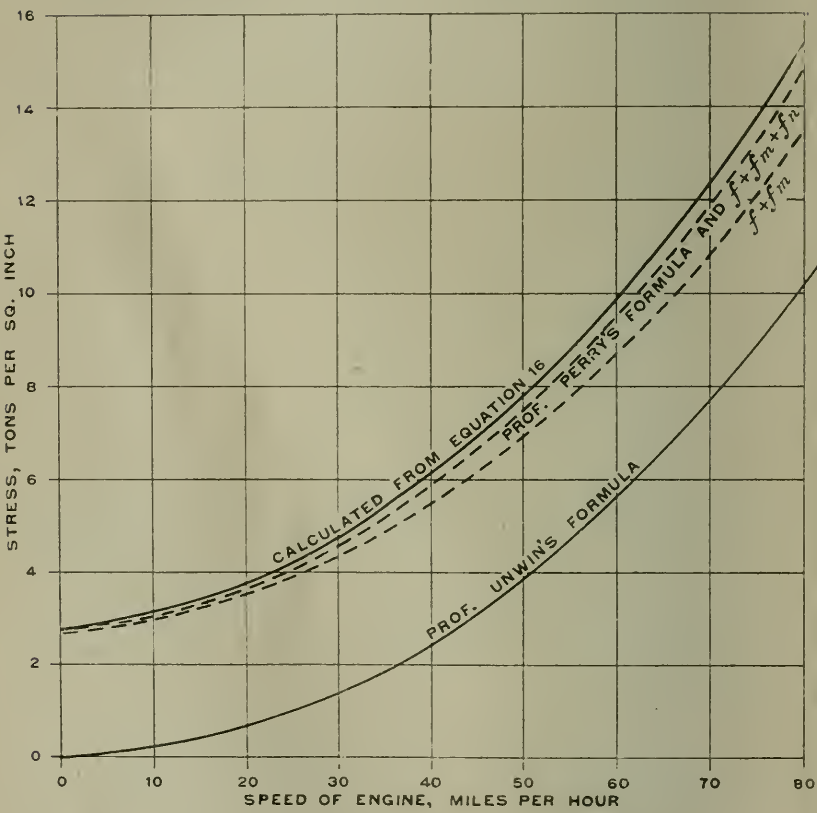
r the radius at which the rod acts in feet,

l the distance between the centres in inches, and

Z the modulus of section in inch⁴ units.

Column 8, Table 2, gives the results obtained by applying this formula to the same rod, and it is seen that the stresses obtained are considerably below those in column 9.

Fig. 3.—*Stresses in Coupling-Rod at Different Speeds of the Engine, Calculated by Different Formulæ.*
Steam-Pressure 160 lb. per square inch.



To obtain the stress from equation (16) is laborious, and the Author would suggest the following method, which will be found to give results in very close agreement with those in column 9, Table 2, and can be easily followed.

TABLE 2.

Steam-Pressure, 160 *lb. per square inch.*

1	2	3	4	5	6	7	8	9
Speed of Engine. Miles per hour.	Direct Stress, f tons per sq. in.	Stress due to uniform Load, f_m tons per sq. in.	Stress due to eccentricity of F, f_n tons per sq. in.	$f+f_m$ tons per sq. in.	Total Stress $f+f_m+f_n$ tons per sq. in.	Stress calculated from Prof. Perry's formula. Tons per sq. in.	Stress calculated from Prof. Unwin's formula. Tons per sq. in.	Stress calculated from equation (16). Tons per sq. in.
10	2·79	0·35	0·05	3·14	3·19	3·19	0·16	3·20
20	2·79	0·84	0·11	3·63	3·74	3·73	0·63	3·78
30	2·79	1·63	0·22	4·42	4·64	4·64	1·42	4·70
40	2·79	2·73	0·37	5·52	5·89	5·81	2·53	6·18
50	2·79	4 11	0·55	6·90	7·45	7·53	3·95	7·70
60	2·79	5·91	0·78	8·70	9·48	9·51	5·70	9 82
70	2·79	7·91	1·03	10·70	11·73	11·76	7·75	12·30
80	2·79	10·41	1·38	13·20	14·58	14·61	10·10	15·20

Consider the coupling-rod to be subjected to a uniform load of $w_1 = w + \frac{w}{g}a^2r$ lb. per unit run, where w is the weight of unit length of the rod.

The B.M. due to this

$$= \frac{w_1 l^2}{8}.$$

The stress due to this B.M.

$$= \frac{w_1 l^2}{8Z} = f_m.$$

The deflection at the centre due to this uniform load is

$$\frac{5}{384}\frac{w_1 l^4}{EI} = \delta.$$

The stress due to the pressure F acting at a distance δ from the axis

$$= \frac{F\delta}{Z} = f_n.$$

The direct stress

$$= \frac{F}{A} = f.$$

Total stress

$$= f + f_m + f_n.$$

Treating the rod in this manner, the results have been obtained for different speeds of the engine when the steam-pressure is 160 lb. per square inch. The results, as shown in column 6, Table 2, agree very closely with those calculated by Professor Perry's formula, and are very near to those obtained in column 9. Hence, either this method or the one suggested by Professor Perry of assuming the rod to bend in a cosine curve can be adopted without any serious errors.

The Paper is illustrated by 3 Figs. in the letterpress.

MEMOIRS.

William Henry Beck was born at St. Helena on 31st December 1835, his father being in the Army of the then existing East India Company, to whom the island belonged at that time. On the death of his father in 1841 he was brought to this country and lived with an uncle, who was also in the Army, at Waterford, and at Rye and Blatchington in Sussex, where his early education was received. In 1853 he came to London and studied engineering at King's College. In 1856 he was engaged as an assistant to classify and arrange the exhibits which were left over from the Great Exhibition of 1851, and it was then suggested that these should form the nucleus of a permanent museum under the Science and Art Department. This idea materialized in 1857, resulting in the establishment of the Patent Museum. Mr. Beck was then a mechanical assistant in the Civil Service, which position he held until 1861, shortly after which year he established the firm of W. H. Beck and Co., consulting engineers and chartered patent agents. He designed all the mechanical details of the first ice skating-rinks, in conjunction with the late Professor Gamgee, amongst which may be mentioned the Chelsea Glaciarium, the Southport Glaciarium, also the old Charing Cross floating baths. Subsequently he was engaged in an advisory capacity in connexion with various refrigerating works, stores, and ice factories. He introduced the system so much in use for cooling milk known as the Elevated Brine Storage System, and also designed factories and machinery for crushing and grinding asphalt. For various Municipal Bodies he also carried out heating and ventilating arrangements in asylums, baths, and wash-houses. He remained the senior partner of the firm until his death, which took place at Brockley, Kent, on 4th July 1915, in his eightieth year. He was elected a Member of this Institution in 1873; and was also a Fellow of the Chartered Institute of Patent Agents.

[The I.Mech.E.]

Herbert Henry Bell was born at Doncaster on 7th April 1882. He was educated at All Saints' School, Gorton, Manchester, and at the Municipal School of Technology, Manchester. In 1895 he began an apprenticeship with Messrs. Beyer, Peacock and Co., Ltd., Gorton Foundry, Manchester, and upon its completion seven years later he became an engineer on the staff of Messrs. Arthur Koppel, of London, light railway engineers. After three years with this firm, he went to Liége as inspector of constructional steel-work for Messrs. Dolphin and Kröhnke, and six months later he acted in the same capacity at Brussels, on behalf of Messrs. Milliken Bros. of New York. He remained at Brussels for nearly three years, and then rejoined the staff of Messrs. Arthur Koppel at their London office, from which position he was appointed as representative for the North of England for the same firm, having charge of their Manchester branch. In 1912 he transferred his services to Messrs. Herbert Morris, Ltd. (late Herbert Morris and Bastert), electric crane manufacturers, Loughborough, and in January 1913 he was appointed by the firm to take charge of the South and West Wales district, having his headquarters at Cardiff. His death took place at Penarth on 26th June 1915, at the age of thirty-three. He was elected an Associate Member of this Institution in 1910.

Edward Joseph Bull was born at Mullingar on 1st January 1872. He was educated at the Royal Academical Institution, Belfast, the Commercial and Grammar School, Belfast, and the Ranleigh School, Athlone. He served an apprenticeship of five years, from 1892 to 1897, with Messrs. Combe, Barbour and Combe, Ltd., Belfast, and in 1898 became manager of the Behar Iron Works, Mozeffurpore. In 1901 he became Chief Engineer of the Seeraha Sugar Works, of which he supervised the erection for the India Development Co., Ltd. From 1902 to 1903 he was chief engineer and managing director of the Empire Engineering Co., Ltd., Cawnpore, and in 1904 was appointed District Engineer, Sarun District. His death took place at Chupra on 18th April 1915, at the age of forty-three. He was elected an Associate Member of this Institution in 1905.

Edward Teshmaker Busk was born at Winchmore Hill, Middlesex, on 8th March 1886. He was educated at Bilton Grange School and at Harrow, and followed a three years' course of engineering at the University of Cambridge, taking the First Class Mechanical Sciences Tripos. In 1909 he started an apprenticeship of two years with Messrs. J. and E. Hall, Dartford, and in 1912 became assistant engineer in charge of Physical Experimental Work at the Royal Aircraft Factory, South Farnborough. It was in this capacity that he devised several valuable improvements in the mechanism of aeroplanes and the disposition of their parts tending to complete stability without material loss of efficiency. By the autumn of 1913 he had carried his researches so far that any aeroplane built to his design would give such a result, and in November 1913 was for the first time able to make uncontrolled flights of several hours' duration in winds up to thirty-eight miles an hour. On one occasion Colonel Seely, the then Secretary of State for War, was his passenger, and he later made demonstration flights before the King and Queen. After flying with Colonel Sykes, the Commanding Officer of the Royal Flying Corps, from the Royal Aircraft Factory, Farnborough, to Salisbury Plain and back, both passenger and flyer leaving the aeroplane to control itself whilst they wrote notes throughout the journey, he persuaded the authorities to take the matter up as having been tested and demonstrated in practical form. Mr. Busk was flying his own stable aeroplane at Aldershot, when, on 5th November 1914, it caught fire in the air, causing his death, in his twenty-ninth year. He had in 1911 received a Commission as 2nd Lieutenant in the London Electrical Engineers, Territorials. He was elected an Associate Member of this Institution in 1914.

John Aiton Charnock was born in the East Indies on 23rd August 1862. He was educated at St. Mark's College, Windsor, and the Edinburgh Academy, Edinburgh. Later he attended classes at the College of Science and Art, Glasgow. In 1878 he commenced an apprenticeship of five years in the works of Messrs. Miller and Co., Vulcan Foundry, Coatbridge, and on its

completion in 1883 he became a draughtsman with Messrs. William Beardmore and Co., Ltd., Parkhead Forge and Rolling Mills, Glasgow. Four years later he transferred his services to the Fairfield Shipbuilding and Engineering Co., Ltd., Govan, Glasgow, with which firm he remained two years, when he was appointed works manager to the Mannesmann Tube Co., Ltd., Landore, South Wales. In 1896 he went to America to take up the position of manager to the Greenville Tube Co., Pennsylvania, and in 1898 he returned to this country and became a partner in the firm of Charnock, Phillips and Co., mechanical and electrical engineers, Bridge Works, Birmingham. In December 1912 he went back to the United States and was employed in the works of The William Tod Co., Youngstown, Ohio, until December 1914, when he returned to this country, and acted as their representative. His death took place very suddenly at his residence in Birmingham, on 30th April 1915, in his fifty-third year. He was elected an Associate Member of this Institution in 1905.

George Cameron Douglas was born at Inverness on 11th March 1856. He was educated at the High School and Royal Academy, Inverness and Tain, and acquired his technical education at the Glasgow and West of Scotland Technical College and the University of St. Andrews. He began his apprenticeship in 1872 at the Highland Railway Works, and in 1878 entered those of the North British Railway at Cowlairs. A year later he was engaged as a draughtsman by Messrs. L. Sterne and Co., Ltd., of the Crown Iron Works, Glasgow, and in 1881 became their chief draughtsman. This position he held until 1883, when he was appointed assistant engineer to Messrs. Thompson, Son and Co., Douglas Foundry, Dundee. While in Glasgow he followed higher courses of engineering at the College of Science and Art and the Glasgow and West of Scotland Technical College. He took the gold medal in mechanical engineering and was for a time assistant to Professor Jamieson. In 1887 he set up in business on his own account as Consulting Engineer and Patent Agent, and soon became an

authority on patent laws, co-operating with others towards their improvement, besides giving evidence on several occasions as an expert before special Committees. In addition to Papers and articles on patent laws, Mr. Douglas contributed a Paper to this Institution on the "Watt Dredger Engine," which was published in the Proceedings, July 1907, page 783. His death took place at West Newport, Dundee, on 24th April 1915, at the age of fifty-nine. He was elected a Member of this Institution in 1903.

Edwin James Dunstan was born at North Tawton, Exeter, on 20th September 1863. He was educated at the North Tawton Grammar School, Devonshire, and later at the South Western Institute and Polytechnic, Exeter. In 1881 he began a six-years' apprenticeship in the Locomotive, Erecting and Fitting Shops of the London and South-Western Railway at Exeter, and on its completion in 1887 he remained with the company to gain further practical knowledge, being employed as express engine driver and also instructor to the drivers' and foremen's improvement class. In 1897 he was appointed driving inspector to the Northern Railways of China, and superintended the erection of the first four express engines of a modern design for the Peking and Tientsin Line. Two years later he became Locomotive Superintendent and Traffic Manager of the Shanghai–Woosung Line. In November 1905 he was appointed Locomotive Superintendent of the Shanghai–Nanking Railway, and in June of the following year he became their Chief Locomotive, Carriage and Wagon Superintendent. In October 1914 he was appointed Locomotive Superintendent of the Shanghai–Hangchow–Ningpo Railway in addition to his other duties. He was one of the original members of the Engineering Society of China, of which he became President in 1912. He received the Chinese Government decoration of the Sixth Class of the Order of the "Chiaho" for services rendered during the recent Revolution in China. His death took place in Shanghai on 25th February 1915, in his fifty-second year. He was elected a Member of this Institution in 1907.

Herbert Henry Ford was born at Bath on 3rd March 1870. He was educated at the Portway Schools in that city, and received his technical education at the Bath Technical School. In 1883 he began an apprenticeship in the works of Messrs. Day and Co., at Bath, and on its completion in 1889 he worked for some time at Liverpool and Barrow-in-Furness, fitting and erecting machinery. For one year he gained sea experience in the ships of the Royal Mail Steam Packet Co., and next was engaged by Messrs. J. and G. Thomson, Clydebank, on boiler erection and trial trips. In 1894 he started in the employment of Messrs. Stothert and Pitt, crane makers, Bath, where he rose to be their outside manager. In this capacity he carried out many important contracts, both at home and abroad, and specially supervised the installation of the mechanical and electrical work on several cantilever cranes of the largest capacity in this country. After about fifteen years' successful work with this firm he joined the staff of Sir William Arrol and Co., Ltd., Glasgow, as outside engineering manager, and in 1913 he became manager of the crane work department of the firm. His death took place on 22nd May 1915, at the age of forty-five, as the result of the railway accident near Gretna, when returning from a business visit to London. He was elected an Associate Member of this Institution in 1908, and was transferred to full Membership in 1913.

Edward Marriott Gibson was born at Ligovo, near Petrograd, on 22nd May 1870. His scholastic education was received at Winchester College from 1883 to 1887, after which he studied for three years at the City and Guilds of London Technical College, Finsbury. In 1890 he began an apprenticeship of four years at the Salford Iron Works of Messrs. Mather and Platt, and on its completion he went as assistant engineer to the Schlüsselburg Calico Printing Co., near Petrograd. Six years later he was appointed chief engineer to the company, and in 1902 was added the post of outside manager. These positions he was holding at the time of his death, which took place at Schlüsselburg on 11th June 1915, at the age of forty-five. He was elected an Associate Member of this Institution in 1904.

David Gilbert was born at Eastbourne, Sussex, on 11th February 1888. He was educated locally and served an apprenticeship of four years with Messrs. R. H. Munro, machine-tool makers, of South Tottenham. On its completion in 1909 he studied at the Northampton Institute, London, where he took the three-years' course in Engineering. During this course he was sent to Messrs. Reavell and Co.'s Works at Ipswich, for practical training, and subsequently was engaged on fitting and erecting air-compressors and steam-engines for the firm. In November 1914 he enlisted in the Divisional Engineers of the Royal Naval Division, and went out to the Dardanelles in the early part of this year as corporal with the 1st Field Company. After being slightly wounded in the shoulder by shrapnel, he caught a chill in the very damp trench, which produced the internal trouble from which he died. He was treated at first in a rest camp, and then passed on to the hospital at Cairo, where his death took place on 21st June 1915, at the age of twenty-seven. He was elected a Graduate of this Institution in 1913.

James Gray was born in Edinburgh on 28th August 1851. His early education was received at George Heriot's School, Edinburgh, and thereafter at the Heriot-Watt College and the University of Edinburgh. He served an apprenticeship of six years at the engineering works of James Dove and Son, of Edinburgh, and from 1872 to 1878 was engaged as fitter and erector at various works in Edinburgh and London. He next went to sea for three years, and then became outside erector for James Milne and Son, of Edinburgh, from 1880 to 1883. In the following year he was engaged on the fitting up of the Engineering Laboratory and the construction of experimental apparatus at the University College, Dundee, after which he worked in the drawing office of James Milne and Son and later in that of the London Road Foundry, Edinburgh. In 1887 he was engaged as tutor for Board of Trade Examinations at the Leith Nautical Academy, and three years later he went to the firm of D. Thomson, Ltd., of Edinburgh, as chief draughtsman, and subsequently became

works manager and director of the company. Fifteen years later he resigned his position to practise as a consulting engineer in Edinburgh. His work lay chiefly in connexion with baking machinery, for which he brought out several inventions. During the last four years he had been teaching in the Engineering Department of the University of Edinburgh, and for thirty years he had also taught in the evening classes of the Heriot-Watt College. His death took place in Edinburgh on 4th May 1915, in his sixty-fourth year. He was elected a Member of this Institution in 1905.

Edward Haile was born in London on 22nd September 1890, and was educated at Wilson's Grammar School, Camberwell. He served a pupilage from 1908 to 1911 under Mr. D. Earle Marsh at the Brighton Locomotive Works of the London, Brighton, and South Coast Railway, and after its completion he occupied various positions in the Locomotive Running Department until October 1914, when he joined the ranks of the Divisional Engineers of the Royal Naval Division, subsequently becoming sergeant. On 29th May 1915, while taking part in the fighting in the Gallipoli Peninsula, he received wounds which resulted in his death on the following day, in his twenty-fifth year. He was elected a Graduate of this Institution in 1911.

William Jackson was born at Keith Hall, Aberdeenshire, on 29th June 1849. Having developed an early liking for engineering, he was apprenticed to Messrs. George Murray and Co., Banff, and later to Messrs. Hall, Russell and Co., of Aberdeen. On the completion of his apprenticeship he went to Calcutta, and, later, to Assam, where he joined his brother, who was manager of the Scottish Assam Tea Co. Soon after, he became assistant to his brother, and subsequently had charge of the tea-house and the manufacture of tea at the central factory of the company's estate. At that time—1870—the tea-leaf had to be rolled by hand, and there was no tea-drying machine in existence in the British Colonies. He saw at once the necessity for improvement,

and before the lapse of many months he had invented a tea-rolling machine, which set at liberty the coolies for other work. He then devoted his whole time and energy to inventing and improving machinery used in the manipulation of tea, and it is greatly due to his efforts that Assam and Ceylon were able to compete so successfully with China in the economical production of tea. His tea-driers are well known throughout the East, and are in use on most of the great tea estates. After his retirement from active life in the East in 1886, he continued his engineering work in Aberdeen, and largely added to the noteworthy record of inventions with which his name is connected. His workshop at his residence was fitted up with all the latest engineering appliances, and many years ago he utilized electricity for lighting and power purposes long before it had reached its present development. His death took place after a severe illness at his residence in Aberdeen, on 15th June 1915, at almost the age of sixty-six. He was elected a Member of this Institution in 1889.

Frederick William Lawson was born at Leeds on 24th June 1845. He was educated at Leeds Grammar School and served an apprenticeship of eight years with Messrs. Samuel Lawson and Sons, Hope Foundry, Leeds, becoming a partner in the firm in 1876. In 1895 he entered the Leeds City Council, where, amongst other municipal enterprises in which he took an active part, he gave special support to the reorganization of the tramway system of the city. In 1900 he became Lord Mayor of Leeds. His death took place at Bath on 24th February 1915, in his seventieth year. He was elected a Member of this Institution in 1882.

William Martin-Davey was born at North Shields on 6th January 1863. He was educated at Aberdeen Park College, London, and received his technical education at the Birkbeck Institute, London. In 1878 he served an apprenticeship of six months in the drawing office of Messrs. Sewards, of Millwall, after which he entered the workshops of Messrs. John Stewart and Son, Blackwall, where he remained until 1883. In that year he was

employed for a short time by Messrs. White and Co., Albert Dock, London, and then sailed as junior engineer in the employ of the British India Steam Navigation Co. until 1886, when he obtained a second class Board of Trade engineer's certificate. He thereupon became second engineer on board a Spanish steamer, and ultimately chief engineer on taking his first class Board of Trade certificate of competency. He was next appointed a ship and engineer surveyor to Lloyd's Register of Shipping in 1887, but resigned the appointment four years later to commence practice as a consulting engineer and naval architect in Liverpool. Subsequently he became senior partner in the firm of Martin-Davey and Herd, of Liverpool. Thinking that there was about to be an immense development of the mercantile marine service of the United States and Canada, following upon the opening of the Panama Canal, he decided to go to Vancouver, B.C., where he opened new offices. In the early part of 1915 he was making a semi-business visit to this country, accompanied by his wife and only son, when all three became victims in the loss occasioned by the torpedoing of the R.M.S. "Lusitania" by a German submarine on 7th May 1915. He was fifty-two years of age. He was elected a Member of this Institution in 1912.

Henry Rofe was born in Birmingham on 15th February 1839, being the son of Henry Rofe, Engineer to the Birmingham Waterworks Co. and Professor of Engineering at Queen's College, Birmingham. He was educated at King Edward VI School and Queen's College, Birmingham, and the Royal School of Mines, London. In 1856 he entered his father's office, and three years later he was appointed sub-engineer to the Birmingham Waterworks Co. In March 1863 he became acting engineer, and held that position until December 1865, when he resigned. His next appointment was as waterworks manager and engineer to the Rochdale Corporation from 1868 to 1874, when he became engineer to the Nottingham Waterworks Co., and held this post until the Waterworks Undertaking was transferred to the Corporation in 1879. In that year he was appointed general manager to the

Southport Waterworks Co., which was, in its turn, transferred to the Southport, Birkdale and West Lancashire Water Board in 1902, when he was appointed consulting engineer to the Board. In 1885 he entered into partnership with Mr. Edward Filliter, and practised with him as a consulting engineer in Leeds and Westminster until 1887, when Mr. Filliter retired. He practised alone until 1901, when he took his elder son, Mr. Henry J. Rofe, into partnership. Since 1884 he had been engaged in over 150 Water Bills before Parliament, and designed and supervised the construction of works for the following corporations and companies: Leeds and Liverpool Canal Co., Rochdale Corporation, Wakefield Corporation, Oswestry Corporation, Kettering Urban District Council, Newquay and District Water Co., Holyhead Waterworks Co., Newark Corporation, Felixstowe and Walton Waterworks Co., Llanelly Rural District Council, etc. In 1893 he prepared, in conjunction with Mr. H. J. Marten, a report to the Conservators of the River Thames on storage reservoirs in the Thames Basin, and gave evidence before the Royal Commission appointed in that year to inquire into the water supply of the Metropolis. In 1905 he reported on the water supply to the Cape Peninsula. His services were frequently in requisition as arbitrator and as an engineering witness in cases dealing with water questions. His death took place in London on 2nd March 1915, at the age of seventy-six. He was elected a Member of this Institution in 1872. He was also a Member of the Institution of Civil Engineers and of other Societies.

James Thomson Smith was born at Carluke, Scotland, on 26th September 1880. He was educated at Carluke Public School and received his technical education at Carluke Higher Grade School, studying afterwards at the Royal Technical College, Glasgow. He served an apprenticeship of five years with Messrs. A. and J. Stewart and Clydesdale, Ltd., Mossend, near Glasgow, now Messrs. Stewarts and Lloyds, becoming one of their draughtsmen in 1903. After holding this post until 1905, he joined the Steel Co. of Scotland as first assistant draughtsman,

but in 1906 returned to Messrs. Stewarts and Lloyds, with whom he remained until the time of his death. From 1910 Mr. Smith was also engaged as teacher of Engineering Drawing in the continuation classes under the Carluke School Board. He had a wide knowledge of engineering generally, but was especially conversant with the economical use of fuels, and the building and working of regenerative gas-furnaces. His death took place at Carluke on 3rd June 1915, in his thirty-fifth year. He was elected an Associate Member of this Institution in 1912.

Edward James Stevenson was born in London on 7th August 1882. He was educated at Streatham Grammar School and served an apprenticeship of four years with Messrs. R. Cort and Son (1898–1902), when he became Manager of the firm, and subsequently Chairman of the Company. He relinquished this position in 1907 to enter the Submarine Boat Department of the firm of Messrs. Vickers, Sons and Maxim, and was holding the post of Manager of the Power Station, Engine, Smithy, and Shell Departments, at the time of his death, which took place at Barrow-in-Furness on 9th May 1915, in his thirty-third year. He became a Graduate of this Institution in 1902, and was Honorary Secretary of the Graduates' Association during 1904–5, and Chairman in 1905–6. He was elected an Associate Member in 1907.

James Henry Taylor was born at Rochester on 3rd November 1869, and was educated at a local school. In 1885 he began an apprenticeship with Messrs Larnder Bros., Bath Hard Iron Works, Rochester, and passed through the various shops and drawing office. On its completion in 1891 he was employed as assistant engineer at the works of the Wickham Cement Co. In 1894 he was placed in charge of the estimating department at H.M. Dockyard, Sheerness, and in the following year became chargeman of engine fitters. Having worked for six years in this capacity, he was appointed inspector of engine fitters, and served from 1908 to 1912 at H.M. Dockyard, Hong Kong, returning to Sheerness

as acting foreman of engine fitters. This position he was holding at the time of his death, which took place at Sheerness on 16th June 1915, in his forty-sixth year. He was elected an Associate Member of this Institution in 1910.

Captain Oswold Neville Tebbutt was born at Cambridge on 15th October 1890. He was educated at St. Faith's School, Cambridge, at Northdown Hill School, Margate, and at the New School, Abbotsholme. He matriculated at the University of London in 1908, and entered McGill University, Montreal, in the same year, graduating Bachelor of Science (Chemical Engineering) in 1912. In the latter year he returned to England, and became manager of the Shepreth Branch of the East Anglian Cement Co., Ltd., and later manager of the Linley Branch. In September 1912 he joined the 1st Battalion Cambridgeshire Regiment, and was gazetted Captain in September 1914. While reconnoitring at St. Eloi he was killed by shell on the night of 15th March 1915, in his twenty-fifth year. He became a Graduate of this Institution in 1914.

Second-Lieutenant John Wilson was born at Cheadle Hulme, Cheshire, on 18th May 1891. He received a general education at schools in Manchester, after which he was a student at the Municipal School of Technology, Manchester, from 1907 to 1910. During that period he received a military training in the Officers' Training Corps. He subsequently obtained the degree of B.Sc. (Honours Division) in Mechanical Engineering at Victoria University. His apprenticeship was served partly with Messrs. Gibb and Hogg, Ltd., Airdrie, and partly with Messrs. Murray and Paterson, Ltd., Coatbridge, makers of iron and steel works plant. In 1912 he went for one year as chief assistant to the late Professor Andrew Jamieson, of Glasgow, with whom he was engaged on general consulting work, and then became assistant engineer with the A. E. G. Electric Co., Ltd., of Glasgow. This position he was holding at the time of the

outbreak of the War, soon after which he received a commission as Second-Lieutenant in the Lowland Division of the Royal Engineers (T.), and proceeded to the Front at the end of January. He was killed in action in France on 9th May 1915, at almost the age of twenty-four years. He was elected an Associate Member of this Institution in 1914.

SOME UNPUBLISHED LETTERS OF JAMES WATT.

Collated by H. W. DICKINSON, *Associate Member*,
of the Science Museum, London.

Nearly a century has elapsed since the death of James Watt, and great as have been the strides made in our profession during that period, yet those who have studied industrial history even superficially cannot help confessing that the progress made in Watt's lifetime was, relatively, as great as, if not greater than, in our own. When we reflect, further, how large is the number of engineers who have contributed to this progress, and yet how few such men lived in Watt's day, our admiration for his genius is justified. That the Institution has been alive to the importance of James Watt's work is proved by the attention devoted to it.*

Granting these premises, it is but natural that we should wish to know more about the man himself—the education that prepared him for his life's work, his struggles, his difficulties, his successes, his joys and his sorrows. There is no better way of learning about these matters than from a man's own pen, and in Watt's case we are singularly fortunate, because a very large number of his letters, both private and business, from about 1765, when he was in his

* *cf.* Cowper "On the Inventions of James Watt, and his Models preserved at Handsworth and South Kensington." Proc. I.Mech.E., 1883, page 599.

thirtieth year, till the end of his long life in 1819, were preserved by those to whom they were addressed, particularly by his partner and friend "the princely Boulton," from the conviction, it would seem, that here indeed was no ordinary kind of man. Watt was an indefatigable correspondent, and, taken altogether, letter-writing must have occupied many years of his life; indeed, it was the drudgery entailed in copying his letters which led him, in 1779, to one of his minor but none the less valuable inventions—that of the copying machine.

A selection from Watt's correspondence was published more than half a century ago,* followed within the next ten years by two biographies † wherein many more extracts from his letters saw the light. Anyone might conclude, therefore, not unreasonably, that everything of real value had been given to the public. When we learn, however, that of the authors of the works in question, one was an advocate and the other a surgeon, we need not be surprised to find that, without casting any reflection on their literary acumen or the technical knowledge that they acquired in later life, they have overlooked a good deal that is of engineering interest. Not only so, but there is a mass of Boulton and Watt documents on all kinds of subjects preserved in the Watt Museum,‡ and there are other papers in private hands, none of which were consulted in bringing out the works cited.

By kind permission of the present representatives of the Boulton family, the collator has had the privilege of looking through the Boulton and Watt MSS.,§ and he is further indebted to them for permission to make use of such letters as appeared

* Muirhead, "Origin and Progress of the Mechanical Inventions of James Watt." 1854. 3 vols. 8vo.

† Muirhead, "Life of James Watt." 1859. 8vo. Smiles, "Lives of the Engineers—Boulton and Watt." 1865. 8vo.

‡ At the Cornwall Works, Birmingham, till June 1915, when the contents were transferred to the care of the Birmingham Central Free Library. The items are quoted thus: "Tangye MS."

§ At their family seat, Tew Park, Oxon. Each item is quoted as "Boulton MS."

interesting. Mr. George Tangye (*Member*) has unreservedly allowed the collator the use of anything in the Watt Museum, which contains practically all the documentary matter of value from the old Soho Works, the contents of which were sold in 1893. Mr. R. B. Prosser, sometime Chief Examiner at the Patent Office, has permitted the use of a collection of letters, dating from 1789 to 1815, written to John Southern * by Matthew Boulton, James Watt, and James Watt, Jun. These were preserved by members of the Southern family till 1890, when they were handed to Mr. Sam Timmins, F.S.A., the well-known authority upon matters connected with the industrial history of Birmingham. The MSS. were given by him to Mr. Prosser.

From this large amount of material quite a small selection has been made, for the purpose of the present Paper, of a few letters representative of as many aspects as possible of Watt's activities. The letters have, naturally, little connexion with one another beyond the fact that they are in chronological order, but an attempt has been made to indicate the purport of each and to explain the allusions in them. It seems to the collator that there would be no better way of doing honour to the memory of James Watt, say, on the hundredth anniversary of his death, than by publishing more of his letters and MSS.

Before commencing the perusal of the documents, the reader would do well to try and realize the atmosphere of the eighteenth century, when our commerce was beginning to extend rapidly, when great industrial inventions were in their infancy, when the foundations of chemical science were being laid, when in the ecclesiastical and political worlds new ideas of Church and State were beginning to emerge, and when, amid the clash of arms, our colonial empire was being established.

Improvements in the Surveyor's Level.—The first letter [Boulton MS.] to be quoted from is dated 12th December 1769, and was

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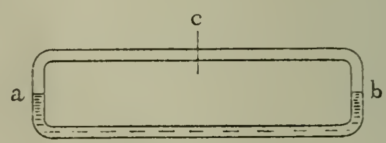
* See *infra*. These letters are quoted "Southern MS." It is understood that they will be placed eventually along with other Watt MSS. in the Birmingham Central Free Library.

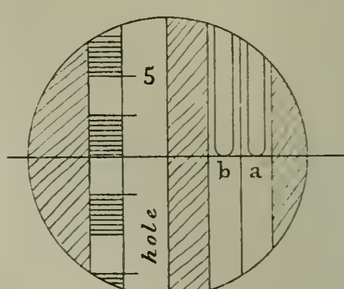
addressed to Watt's friend, Dr. William Small, of Birmingham, a man of great ability, who died before his prime, a few years subsequent to this date. He it was who introduced Watt to Boulton :—

If I was to follow the business of levelling I should certainly make some more alterations on levels, for, from different causes while you are looking thro' the telescope it is possibly altering its situation. This you cannot know till you remove your head and examine the level & if it blows or the ground is soft you can never be certain take what time you will & I assure you this circumstance kills not a little time not much to the comfort of the observer whose cold fingers & toes urge him to be gone. By the by I got a violent toothache & lost a tooth by this very thing about a fortnight ago. Now if this bubble [?] would travel [?] faster & could be seen at same time with the object it would remove this inconvenience and would render the operation more certain.

I propose to take a glass tube $\frac{1}{10}$ inch dia^r. & bend it into a parallelogram 18 or 20 inches long & 2 inches wide & fill it with spirits to a & b then join it hermetically at c. Now if I see the 2 legs [?] a & b in a line with any third object that object is level with my eye. Now take a four glass or day



telescope whose ob[ject] glass focus = a. b. cut a slit in it in the focus of the first eye glass to admit the leg b & another where it answers to admit a. The leg b will be seen erect and magnified & if a fifth glass or rather a segment of a glass be introduced so as to form a telescope by which you can see the leg a erect and of the same size as b you will have the thing desired. for the



motion of the liquor in the legs a & b will be just equal to the motion of the picture in g[rea]t foc[us] : ob[ject] glass & will be magnified as much by the eye glass (you will easily conceive the adjustment necessary here) the field will have this appearance. The surfaces of the liquor have all the necessary sharpness but I have at present no time to try any further experiments.

At the time this letter was written, Watt was practising as a civil engineer and was in a fair way of becoming one of the leading men of his day in that profession. At the same time he was devoting what little leisure he had to the development of his steam-engine which he had patented in the January previous. His keen inventive capability is seen in his suggested improvements in the surveyor's level. It is a remarkable fact that the idea here schemed out for bringing the bubbles of the level on to the staff so that at the moment of taking the observation the surveyor might see that his instrument had not shifted, has only within the last decade been brought out as quite a new thing. It may be conceded freely that it has been done in a much neater way than Watt suggested, but the anticipation is there and is certainly typical of his inventive genius.

Offer of Appointment in Russia.—The next document [Tangye MS.] to be reproduced is the draft of Watt's reply to a letter dated April 1771 from John Robison, afterwards Professor of Mechanics at Glasgow, and who was then at St. Petersburg, asking Watt if he would like the post of "Master Founder of Iron Ordnance" to Catherine II Empress of Russia.

The draft is as follows:—

The proposal you make me is highly flattering both to my vanity and Ambition. To my vanity from the opinion you have of my abilities and to my ambition from the Honorable office in which you wish me to be placed.

I find myself however, obliged to decline the acceptance of it Both from being sensible that I by no means merit your recommendation and from my advancing in the estimation of mankind here as an Engineer.

You are also well aquainted with my melancholic constitution; I know not how far the Climate of Russia might agree with it, But granting it to be the same as here—want of success in my experiment might throw me into a despondence of mind highly prejudicial to the Affairs entrusted me.

I therefore beg you to excuse my refusing your offers and to make an Apology for me to your noble Employers, giving them in my name the most Gratefull Thanks for the Honor they have done me.

A second attempt, a few years later, to induce Watt to go to Russia met with a like refusal, although the salary offered—£1,000 a year—must have been a temptation. It is easy to imagine that the world would have been a different place to-day if Watt had gone to Russia and had to give up, owing to a breakdown in health or for other reasons, the prosecution of his invention.

Partnership with Boulton, and Second Marriage.—The next letter [Boulton MS.] to be quoted was addressed to Matthew Boulton, when Watt was back in Glasgow clearing up his affairs before removing permanently to Birmingham, where he had just commenced his celebrated partnership with Boulton, and where he was destined to accomplish his life's work. More important to Watt just then was the fact that he was taking unto himself a second wife—Anne Macgregor—daughter of a dyer in Glasgow. The letter is as follows:—

Glasgow, July 3rd 1776

Dear Sir,

I have hoped to have heard from yóu how matters move but have hoped in vain. I should nevertheless have wrote to you oftener if I had had anything material to communicate. I expected when I left you to have some business to do here sufficiently disagreeable to counterbalance any pleasure I had reason to expect. I have not found matters much more agreeable than my fears & I have still some to go through of the same nature. I have however the pleasure amidst all this to have obtained both the young lady & old gentleman's consent to take her along with me, but [I] shall be obliged to wait a little until she can be ready. This gives me pain as I am sensible I must be wanted with you, but I hope you will excuse it when you consider my situation & that it will save another journey which must otherwise have taken place soon. The only disagreeable part of the business that remains to be done is the settlement & I find that the old gentleman wishes to see the contract of Partnership between you and I, and as that has never been formally executed, I must beg the favour of you to get a legal contract written & signed by yourself, sent to me by return of post or as soon as may be. Lest he should have called my prudence in question I have been obliged to allow him to suppose such a deed did exist but was single, so what

you send must pass for a duplicate and another may be actually written which I hope you will not doubt of my readiness to execute as soon as I return and in fact this deed should have been executed long ago, in common prudence upon both sides, particularly upon yours who have no legal assignations to the Act of Parliament. I therefore hope that you will excuse the old gentleman's caution. If you do not chuse to send the deed itself, you may have a scroll of it made out without date which you may send as the copy the deed was drawn from.

But what I would wish most is your own presence here and the deeds along with you, if your business would permit. I am sensible of the inconvenience such a journey must be to you, but it is a good office I hope I shall never need again and may be of service to me and perhaps to yourself.

If you should decline this proposal & wish to meet me at Carlisle or Kendal fix your day allowing reasonable time for me to receive your letter & make the journey & I will meet you there. From hence to Carlisle is two days jour ney & to Kendal 2½ days. Now you will do in all this as you judge most proper, but I beg you will at least write by first post & when you send me the paper send along with it an Ostensible letter which let be the cover. Whether a man of the world such as you look upon my love as the folly of youth or the dotage of age, I find myself in no humour to lay it aside or to look upon it in either of these lights but consider it as one of the wisest of my actions, and should look upon a disagreement in it as one of the greatest of my misfortunes. but let that pass, You are a very bad confident in love affairs, You look upon them as too good things to be kept to yourself.

If you should chuse to come by the stages, your way is to Sheffield then by chaise to Doncaster where you will find the Newcastle Fly by 12 o'clock comes to Buroughbridge that night & Newcastle the next. The Edinburgh coaches leave Newcastle upon Tuesday and Thursday [and] reach Edinburgh that night. There are stages every day from Edinburgh to Glasgow. Or you may come in the Kendal Stage & take chaise to Carlisle from which twice a week diligence to Glasgow & three times to Edinburgh. I will not urge any further what I have said. You see the necessity of it to my happiness and I am very sensible of your good will towards me.

Now for something comfortable. I have had better health since I left you than has been my lot for years and my spirits have borne me through my vexations most wonderfully. I have lost all dread of any future connections with Mons^r^. la Verol [i.e. small-pox], and if I carry my point in this matter I hope to be very much more useful to you than has hitherto been in my power, the spur will be greater. I have undertaken an engine for my friend Mr. Colevile at Torryburn in Fife of which particulars follow:—

$$\left.\begin{array}{l}\text{Pump 12 inch bore to 92 yds}\\ \text{7 inch} \ - \ - \ \text{40 yds}\end{array}\right\}\ \text{Cyrs 44 inches load } 10^{\text{Hd}}$$

Load in lbs 15533. Coals 2/6 per ton at the engine

Time of going 12 to 16 Hours in the day

P Engine same big pumps & Cylinders

Depth 52 yds. burns 27 tons per week & works 20 hours per day. Terms proposed ⅓ savings & such further sum as I shall judge fair for our trouble.

A person is to be dispatched immediately at his charge to study under Monr. Perrins or Harrison the art of construction & using & to stay with us 3 months. He is bred a carpenter & cabinetmaker & has wrought in the latter branch in London. He is to set out next week 11 July. If you go from home please leave orders what college he is to study at. Sir A. Hope also wants an engine. I am to meet him on Monday to talk with him and shall also cause him send his man to study if we agree upon terms.

As may be inferred from this letter, the cautious old gentleman —Mr. Macgregor—before parting with his daughter was anxious to have a marriage settlement executed, and was desirous, naturally, of seeing the deed of partnership between Watt and Boulton. Hence we learn the extraordinary fact that this document, upon which so much depended, had not even then—more than a year after the beginning of the partnership—been formally executed, such was the entire confidence of Watt and Boulton in one another.

The way in which Watt proposes to get over the difficulty is amusing, but shows real anxiety lest his future father-in-law should get to know how lacking he was in business instinct—a lack which might have convinced the old gentleman that he was not a fit and proper person to whom to entrust his daughter.

Boulton extricated his partner from his little difficulty very ingeniously, as may be seen by a letter already published,* by saying:

"I would without hesitation have sent you the assignment and the article of partnership, had it been in my power; but Mr. Dadley, the lawyer, is suddenly called to London and it cannot be had before his return; but if you want to show it to any of your friends, you may give them a copy of the following heads, which I have extracted from our mutual missives, and are to the best of my knowledge all that our articles contain."

Boulton then proceeds to give the articles of agreement.

* Muirhead, *loc. cit.* II, 98.

The latter part of the letter shows how Watt's health had begun to improve with his new prospects in life. Letters already published show that his mental condition before his partnership with Boulton was one of extreme irritability, due to the fact that in order to earn his bread and butter he had to mark time, so to speak, while his valuable invention of the separate condenser was languishing for want of the time and the capital to devote to it.

The last paragraph in the letter is interesting as showing the terms on which the new engine was sold—that is, one-third of the value of the annual saving in coal attained, together with a sum for drawings and instructions for setting the engine to work. For this last purpose a workman is to be sent to Birmingham to learn his duties, hence Watt's humorous reference to the "college"—that is, shop where he is to work—and to the workmen Perrins and Harrison in whose charge he is to be. In fact, when Boulton and Watt commenced business, they were really what we should call now consulting engineers. It was stress of circumstances and lack of competent workmen which obliged them to take up the manufacture of their own engines.

Success of Watt's Engine.—The next letter [Tangye MS.] is addressed to Boulton, and shows Watt in a sanguine mood over the success of one of his first engines—that at Bedworth Colliery. He discusses also the engine for Chacewater, the first of their construction in Cornwall:—

Bedworth, Feby 28th 1777.

Dear Sir,

It is now clearly determined that Behemoth neither has nor shall stir his tail in the month of Feby 1777—— Some Engineers talk of putting in Steam to try the joints tomorrow, If they do they must be busy, If they wait till the Lord's day & have his assistance I don't know what they may do, but you need not think of coming bringing nor sending any body here untill I bid you otherwise they will only see a standing engine—Old Jonathan [? Hornblower] is to make their engine to use only 7 tons of coal p^r^ 24 hours if so our gains will be moderate—— Your late Attorney here Mr. D——y [? Dadley] has it seems been much worse than Dr. Dodd * Many bonds of his

* Dr. Dodd's defalcations were notorious, *see* Dict. Nat. Biog.

fabrication, names & all have appeared & yet the rogue was worth nothing so much for high living—— It will be necessary instantly to provide Good piston rod Iron, we immidiately want several small ones What appears to me best is immidiately to write to Cleobury forge to draw some of their very best tough into eight square barrs of the following sizes—

2 barrs 6 feet Long each $2\frac{1}{2}$ diameter, for Chacewater
4 barrs 6 feet Long each 2 diameter Shadwell & Soho
4 barrs 6 feet – – $1\frac{3}{4}$ diameter
8 barrs Do – – $1\frac{1}{2}$ square or eight square for sundries

lett the Iron be got with all expedition & I shall so soon as I come *gloriously* home contrive the means of manufacture

It [is] now possible for you to bring the Ladies with you as the ground has got dry, if it keep so, and I shall try to gett an 18 oared barge laid at Longford against the day of the firey trial—— On consideration I still think that we should erect young Chacewater for surely the owners will not be such fools as to throw away a new engine * which has cost them £1000—and if they should if they use the engine a twelvemonth we should get near £300 by it—I think comparing it with York buildings † second Engine ‡ which is nearly of the same power & uses 4 or 5 bushel p^r hour—I believe the latter quantity—that we should gett 1/- p^r going hour or thereabouts—— It is impossible for me to do anything in the drawing way here for setting aside that I have no place but the parlour where the ladies always are—I come home commonly after 4 or 5 oclock without my dinner which I then eat heartily and immediately after get heavy legs which you know to be a certain consequence of cramming oneself yet who can resist when hungry and good meat & drink in the way I expect to hear from you tomorrow before I send this off——

Worries caused by Assistants' Mistakes.—The next letter [Boulton MS.], addressed to Boulton, shows Watt arrived in Cornwall for the second time, and at once deeply immersed in the minor details of the engine business and the worries that the mistakes of his assistants caused him. A cylinder cover that was cast three times, and after all would not do, throws a vivid light on the art of founding of the period. Watt was driven to send for it to John Wilkinson, about the only man at that date who could do any intricate foundry work:—

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* i.e. the one just built by Smeaton. Full details and drawings of this engine, considered to be one of the finest examples on the Newcomen principle ever built, may be found in Smeaton's *Reports*, Vol. 2, pages 347–360.

† On the site of the present Adelphi.

‡ Also of Smeaton's construction.

Redruth, June 27th 1778

Dear Sir

I wrote you on Thursday, I am very uneasy at not hearing from you—— Mr. H: (i.e. Henderson) writes me that Information had been laid against Hall as a smuggler I don't at all doubt of the fact and think it deserves the strictest enquiry and severest treatment which can be inflicted without application to public Justice, he has behaved shamefully and shame ought to be his punishment and you ought to seize those things he has made of our Iron & time and I dou t not but the smiths will be his willing accusers——

If it were necessary to add anything to the catalogue of Blunders delays and ommissions he has been guilty of lately I could mention some instances I have not yet troubled you with—— He has been the occasion of so much trouble and uneasiness to me personally that you must excuse me for entering my solemn protest against his being any longer retained in our service in any *station whatsoever*. He writes me in his last Mr. Johnston wrote him that Wheal Union Gudgeon was sent off on y^e 29th of April It was ready and ought to have been sent off a month sooner & he had repeated orders from me to see it done—— I would not be restrained from turning him off neither by the mean fear of his doing us mischief nor by the want of one in his place I would recall Playfair who can do part of the business & I think now you are at home you can contrive to gett him proper assistance—— I must warn you that Playfair is a blunderer but I dare say he will be assiduous and obedient and plain directions must be given him. Henderson writes me that he has heard of somebody at London likely for y^e place pray god he may answer otherwise we must give up our Soho branch of the business——

Dudley has committed a capital mistake in placing Wheal Union Cylinder one foot too high which will cause the Roof of y^e house to be lifted and the (?) built upon—— The Lid for Chacewater Cyl^{dr} has been 3 times cast here and after all will not do I must send to Wilkinson for one, but I believe the last cast will make shift till it come—— Hallamanin's people have ordered their goods down the Severn & I hope you will take care that the Soho part is not behind the rest as usual—— Copper ores are falling in price Daily & every body very low spirited about it Wheal Virgin is still half full of water & likely to be so They are sinking at least £1500 p^r month——

I am quite tired with riding yesterday & walking to day so must content myself with writing only the necessary

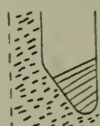
I ever remain

Dear sir your's

James Watt

Metallic Piston-Packing.—The next excerpt [Boulton MS.] is from a letter to Boulton dated Truro, 3rd August 1778. The occasion was that of Watt's second visit to Cornwall on behalf of the firm; as usual he was anxiously absorbed in the engine business:—

In spite of what Mr. H[enderson] says about the leads sticking I have used them both at Chacewater and Tingtang where they have not stuck yett nor showed any dispc^{n} [i.e. disposition] that way although Tingtang piston has a more acute angle than any we have made lately—— I fancy their sticking is caused either by their being in too short pieces, or their not exactly suiting their place or by their being too hard pressed upon by the oakam or being fast between the perpendicular part of the piston and y^{e} cyl^{r}. They ought to be thus



But to prevent any future Bungling lett them be made of good Brass, Copper or gunmetal. They will not ammount to above 60 pound weight for a 63 inch Cyl^{r} and will last a long time In large Cylrs their should be 8 in y^{e} circumference & only 6 in y^{e} smaller ones

the slopes where they join ought to be 3 times the depth in length I am to get £386 from Tingtang the end of y^{e} week—— Both the Engines go on exceeding well and give great satisfaction Chacewater goes 14 strokes p^{r} minute of 9 foot long each and burns about 128 bushels p^{r} 24 hours The water has sunk 12 fathoms in y^{e} mine and it will fork the first lift this night no cross [?] accident of any note has happened except the bursting a pump at Tingtang which was soon rep^{d}. [i.e. repaired].

This excerpt shows how very soon the eternal question of piston-packing cropped up. We have here what is quite the earliest instance known to the collator of the application of metal for the purpose. The packing consisted simply of bearing metals in short wedge-shaped segments with overlapping joints placed next to the cylinder wall. The necessary elasticity behind the segments was given by ordinary oakum. The engine at Chacewater

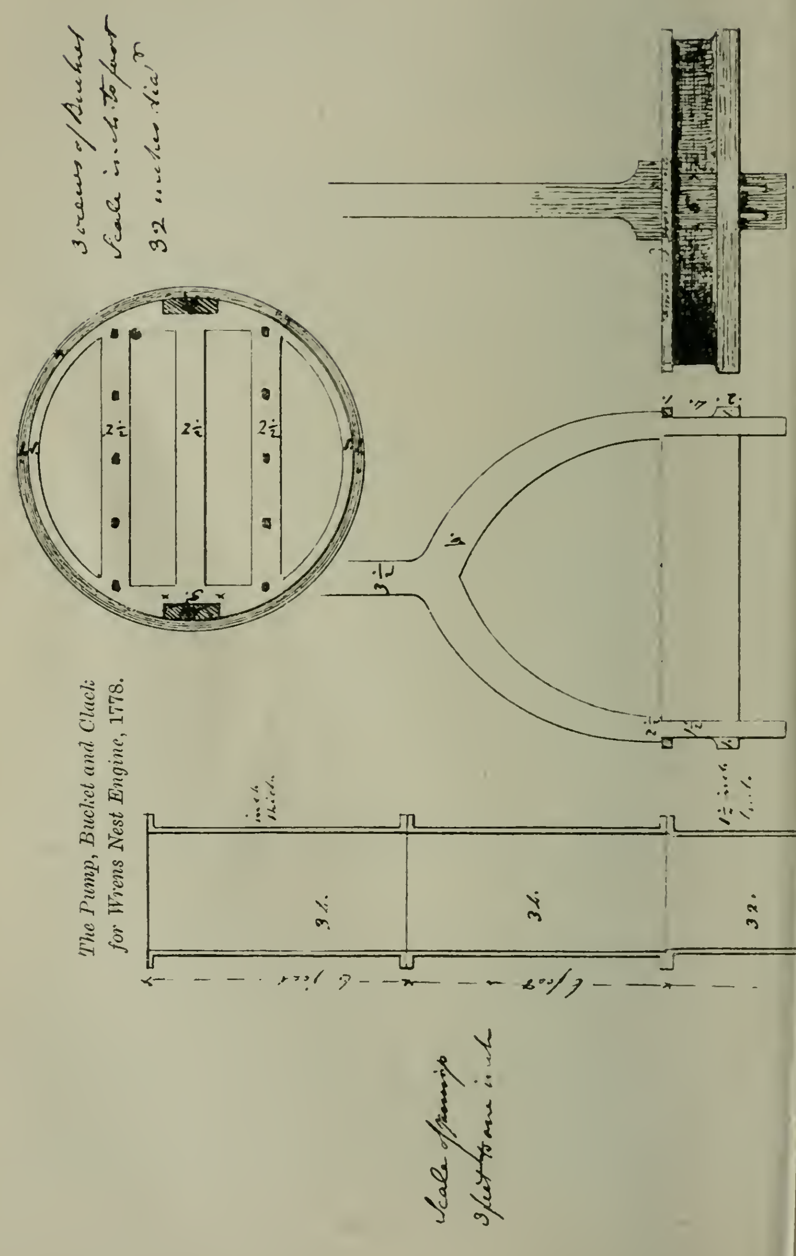
was important, not only because it was the first of Watt's construction in Cornwall, but also because by observations upon it was settled the premium which Boulton and Watt determined to charge for the use of their patent.

Engines and Engine Troubles.—With the next letter [Boulton MS.] quoted from, Watt sends a drawing of the pump, bucket and clack for the engine at Coalbrookdale Ironworks. The drawing is reproduced (pages 500–1) as a specimen of his everyday draughtsmanship at this time. He relates his troubles with the Chacewater engine and also gives instructions for making joints in steam-pipes, etc. :—

Redruth, Aug[t] 13[th] 1778

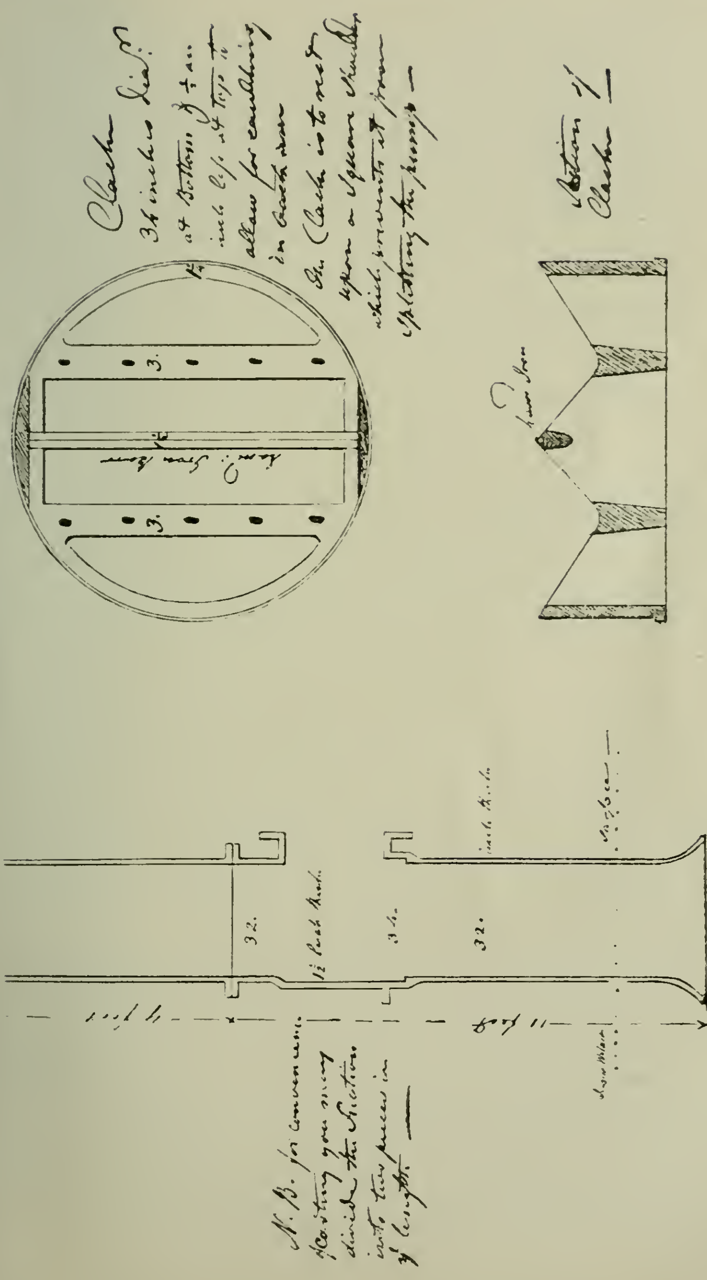
Dear Sir,

On the other side please receive drawing for Wrens nest pump & Bucket & Clack, which please cause copy and transmitt to them [i.e. Coalbrookdale]—— Mr. Onions proposes the pump 34 feet long I have drawn it only 32 as there is no occasion to have more than 2 feet under water when made with a Bell mouth—— I have no notes of the height they want to raise their water but suppose it to be 30 feet at highest—if it be more the dia[r] of the pump should be made less by an inch as our Engines will not go swift when loaded to 11 pounds p[r] inch and it will probably happen that they will want to go swiftest when y[e] waters of Severn are lowest—— I have just looked into his estimate & have calculated the two first articles to show how fare he is mistaken in them, but have not time nor spirits to go through the whole—— The Beam straps straightened out would be 10 feet long each 1¼ thick by 3 inches broad & would weigh 120 pounds each both 240—— The Glands 16 inches long 5 by 2 40 pounds each, in all 320 pounds——each pair of Martingales would weigh 168 pound The Boyler he has calculated near the truth—— The rest I have not ex[d] but any person can do it by the dimensions allowing 4 Cubic inches to the pound—— As to prices of forged work I think it rather high we gett a whole Engine done here at 3¼ [i.e. pence] p[r] pound very good work but strong and heavy—— The beam straps if made of English iron should be a little stronger than order say 1½ by 3 inches and ought to be faggotted up of thin barrs as also ought the martingales or other Capital pieces —— The prices p[r] pound ought to be agreed for & the work weighed the worst expence that could happen would be the having anything too slight rather lett the errors be upon the other side I suppose he cannot do the work altogether under ½ to gett by it at any rata he should have price sufficient to make good



The Pump, Bucket and Clack
for Wrens Nest Engine, 1778.

(Continued from above.)



work—his castings are sufficiently cheap—— since I wrote you last Chacewater Engine wore a very gloomy aspect, as though going eleven strokes per minute it went sluggishly it could be forced on neither by Steam nor by counterpoising a part of the weight, this was the case Saturday all day. On Sunday the disease increased and when I came to it in y[e] evening it was taking more injection than y[e] ▽ [i.e. water] pump could discharge and going extremely heavy though y[e] vacuum was 27. I took off y[e] injection alltogether it mended a little but still drew full pump, concluded a leak in y[e] condenser caused in y[e] first place examine y[e] injection valve found it staked open by a piece of wood on removing which the quantity of injection was reduced but no amendment except bringing it to 12 strokes p[r] minute, at which rate went till Monday when had a general review, beginning at y[e] nozzle found the upper & under regulators both leaked some steam for which tinning their edges was prescribed——my suspicions from y[e] beginning were very strong that we had y[e] Bloomfield disease of a bitt in our throat, but as after that accident these copper cones had been ordered to be rivetted on, I thought it could scarcely happen again & thought perhaps a board, a bunch of oakum, some body's hat or coat had been left in y[e] cylinder & had come into y[e] nozzle and was about to search for it, but first lifted out y[e] exhaustion regulator when behold the copper cone, which had neither been rivetted nor well soldered, lay upon y[e] guard——it was needless to search further, so we tinned the regulators and went to work immediately 13½ strokes to y[e] minute and these performed with vigour—— We take now exceeding little injection, as in the new construction of the water pumps, they do not go to the bottom of y[e] condenser by 5 or 6 inches, so upon y[e] first letting y[e] steam into y[e] induction pipe it forces y[e] remaining injection, (from last stroke) into y[e] air pump and follows it itself up through the water it finds there and is principally condensed in y[e] air pump by y[e] water which had served before—— This operation is performed with so much violence that it lifts the air pump bucket at least 2 inches and letts it fall again before the engine begins its stroke. On tuesday I went to W[l] [i.e. Wheal] Union which goes on slowly & y[e] report of stopping still prevails—— Y[e] matter is to be settled today, the result [I] shall inform you of & want your advice what we should do if they stop——

On Wednesday morning at one o'clock Chacewater tye lift pump rods broke again at a joint, which had never been sound, so much for 3½ work This stopt the engine till one o'clock in y[e] day when I saw it again at work in good order. During y[e] stoppage y[e] water rose six feet in y[e] mine and was then 20½ fathoms below Addit, is probably 2 fathoms lower now—— The Engine burns 1¾ wey * p[r] diem minus one weigh in y[e] week.

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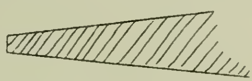
* The wey or weigh of coals as understood by Watt was 72 bushels (say 3 tons), *see* p. 506.

The Conoissiurs say we shall never fork y^e water, or *if* we do we may fork any thing as y^e water is reckoned the heaviest in y^e whole county. I have [?] To make y^e Joints of the Cylinder, nozles Eduction pipe Condenser & other Steam joints, cut with a Chisel pieces of thickish pasteboard the whole breadth of the flanches and pierced for the screw holes, thin these pieces at the ends where they lapp upon one another then soak them in hot water untill they become very soft —— Then take very thin putty made with good raw Lintseed oil & fine ground whiting well mixed, and lay it pretty thick on both sides of y^e pasteboards——put them in their place and then screw the joints together very close—— If you can warm the Joint by any means it will go the Closser—— 24 hours after go round the joint and heave up every screw as tight as may be—— Then take a Caulking Chisel about an inch broad and



Caulk the Joints as hard as you can—— If any Joint requires more than 2 thicknesses of pasteboard to make it up, run lead in y^e joint then take out y^e lead and putty both sides of it with thicker putty than you used for the pasteboard & screw y^e Joint together upon it, afterward caulk up the edges of y^e Lead; but use no lead except in cases of necessity All the screws ought to be lapped with oackum in the shanks so as perfectly to close the holes

Further Engine and Pump Troubles.—Our next excerpt [Boulton MS.], dated August 22nd 1778, from Redruth, finds Watt in the midst of engine and pump troubles :—

. . . . We have [got] into misfortunes at Chacewater, for w^ch in your country y^e Engine would have been blamed which is not the case here—— On Tuesday morning the Bucket wanted to be changed in y^e sec^d lift—in drawing it y^e rope broke & souse down went the Rods & fixed themselves below y^e working Barrel too fast for 2 Capstanes and 40 men to stir them. At last by the help of y^e Engine they were drawn but stuck fast enough to lift y^e whole lower tire (i.e. lift) of pumps along with them untill the stays held them fast. A new bucket was put in and y^e Engine set to work again in seeming good order which continu^d untill Thursday morning when all at once that lift ceased to draw water. The Clack was blamed; drawn & changed. The Engine went about 50 strokes & all as bad as ever, after much difficulty that was also drawn & changed but no amendment. The leather of 3 buckets, following, was found cut off on one side by the few strokes the

Engine went—from w[ch] we suspect that y[e] working barrell is burst, or at least the Clack door piece yesterday evening they sett about drawing the lift w[ch] was expected to be a matter of great difficulty The working barrel cost £200 being of Brass and cannot soon be replaced, except by the one belonging to the 3[d] lift which they intend putting in to keep the water down in the meantime—— The water rises 2 fathom in 24 hours, and we can only sink it about 8 or 9 feet when in good going so that this accident will retard us much—— It was yesterday rose up to 10 fathoms from top of lower lift——

It was determined at W[l] Union meeting that the mine should go on so they are working with life & expect going next week—— I was at Bonze's double engine at W[l] Prosper which is most exceeding well executed & has got the water down The one goes 10 & the other 15 strokes p[r] minute when at forced work and 8 & 12 when in fork & *is said* to burn then only 180 bushels of coals p[r] day Cy[lr] 60 & 48 6 feet stroke——

I wrote you that Mr Meason objects most strenuously to having Mr H[enderson]. He says he has been told that H. was of no use at Torryburn & would not have got the Engine sett agoing without his man Symington & that therefore he cannot be answerable to his employers for having him and would rather have some operative man as he has already too many Gentlemen Overseers—— I am afraid that H's operations at Torry[n]. gave too much reason for this, and the tongue of malice has heightened the picture—— Be that as it may it would be using it very ill to send him to any place where there was such a want of Confidence in him & where y[e] comm[n]. miscarriages would be exaggerated to his predjudice—— Besides I know his accommodations would be very bad & I am sorry to hear his health continues bad—— I therefore this day wrote to Meason that he shall not be sent, but that we have nobody else fitt [for] the purpose but who have prior engagements so that he must put up with the abilities of Symington whom he is so full of—— I shall send such directions as will keep them out of great Blunders and lesser ones must be corrected the first opportunity we have of seeing it—— I send now drawings of the proper curves for the opening arms of y[e] exhaustion for 4 Engines & also drawing of the injection working gear we use at Chacewater which answers hitherto very well and better than any we have yett had—— These you will please get copied with speed and transmitted to their several destinations—— The curves of the arches are Ellipses the foci of which I have marked 'F,' but as this ought to be a secret of state I must entreat you to copy the curves yourself which you can easy do with a silk thread and two pins in y[e] foci * If have not time may cause prick em through but y[r] utmost care should be taken that they be exact as

* The letter contains a rough sketch of half an ellipse, showing how to strike it in the way described.

the figure affects the power more than you can readily conceive even to the half of the weight when compared with a circle—— A valve 10 inches dia^{r} at Chacewater requires only 120^{lbs} to open it at a Lever of 6 inches—— Must press dispatch in y^{e} copying and forwarding these drawings which [I] would have done myself but have no time except when I am too tired to do anything correct I believe Mr. Henderson has copy of Wanlockhead working gear which should be forwarded immediately to Edinburgh inclosed in a tin case I shall scratch off copy of Byker eduction pipe and send to Henderson to prevent mistakes in putting in y^{e} pipes & shall so soon as I can send *more* general directions for putting together, meanwhile he should be advised to have a coppersmith or good plumber to do his soldering it is shamefull to have that leaky—— The engine men here do it exceedingly well—— Have just rec^{d} advice that the work barrel at Chacewater is splitt 4 feet in length I must go there this afternoon to see if it can be mended—— They have got in the other & will be at work tonight again. If nothing call me off tomorrow shall write full directions & send off on Monday——

Hope you got drawings of Wrens nest pump, & directions for joint making sent you on 13th—— Mrs. W. Joins in comp^{ts} to all friends & I ever remain

Dear Sir

Yours sincerely

James Watt

I think it would be cruel to tell Henderson the cause of his not going to Wanlockhead.

The references to Symington are not to William Symington, so well known in connexion with the steamboat, because he was only 15 years of age at the time, but are to his father, who was engineer to the Wanlockhead Lead Mines.

Duty performed by the Atmospheric Engine.—The next letter [Boulton MS.], dated a week later, is interesting, if only on account of the scraps of information about tin mining in Cornwall, and about the performance of the atmospheric engines there:—

Redruth, Augt 29th 1778

. . . . With all the faults of y^{e} Cornish people I think we have a better chance for tolerable honesty here than elsewhere as their meetings being public they will not chuse to expose themselves any farther than strict dealings may justify and besides there are generally too many to cabal—— I am exceedingly vexed at Byker peoples mismanagement but our intolerable delay in sending them assistance justifies them in proceeding in y^{e} best way they could——

As to the Joint making I do not object to yours, but the other is easier and answers perfectly for y^e^ superabundent oil of y^e^ putty soaks the pasteboard nearly as perfectly as if soaked in y^e^ oil itself and the water softens the pasteboard more than the oil does—— The principal thing is y^e^ using only one thickness of pasteboard as if two having them both of y^e^ full breadth of y^e^ flanches——

I am astonished at the carelessness and stupidity of y^e^ Bedworth director, and I beg and *expect* that so soon as everything is done to that engine that you will instantly proceed to trial before creditable witnesses and if possible have the whole brood of their engine men displaced If any others can be procured, for nothing but slovenliness and malice is to be expected from them. At any rate send some steady person there to superintend the working for a week or two that a true average of the fuel may be ascertained upon oath—— Their tardiness and others to settle should make us obstinate in not taking in hand any Engine untill a positive Legal agreement be signed, and for my part you must excuse me when I tell you that I will not put pen to paper on a new subject untill that is done. Untill we have ordered the engine our power is greater than that of the Lord Chancellor as I believe even he cannot compell us to do it unless we chuse lett our terms be moderate & if possible consolidated into money *a priori* and it is certain we shall gett some money, enough to keep us out of Jail, in continual apprehension of which I live at present——

As Wh^l^. Union will probable be going next Monday or tuesday I think you should be turning your thoughts to a journey here and the final settling of all the agreements in this county—— Chacewater Engine is our capital card for should it succeed in forking the mine all doubts will be removed and by having two Engines of same size one lightly loaded and the other fully we shall be able to fix the premium p^r^ Cubic foot x by the depth and proceed without further trials & by attending to the business of this county alone we may at least live comfortably for I cannot suppose less than 12 Engines will be wanted in two or 3 years but after that very few more as these will be sufficient to get ore enough but you cannot reckon the average profits to us above £200 p^r^ engine.

I mentioned to you in my last that we were asked to adventure in W^l^ Union——particulars are as follows there are two mines Owen Vain which is an extensive Copper mine, produced last £1000 p^r^ an^m^ profits, has a common 67 inch Engine 16 inch working barrel to 38 fathoms 6 feet stroke 8 p^r^ minute when in fork and burnt 1¾ wey p^r^ 24 hours i.e. 126 bushels—— The Engine is not a very good one though new—— Tregurtha down where our Engine is placed is upon the same Lode about half a mile distant and consists principally of 3 or 4 Courses of Tin not exceeding rich but must be wrought along with the other on account of the water The profits must arise

principally from Owen vain & wheal park wh^{ch} is a part of it, Blewett & Co have near one fourth of the whole The rest in many hands—— About 5 or 600 miners must be employed to make it profitable as they must now do double the business they formerly did—— They have brought in an Addit to Tregurtha 8 fathoms lower than the old one which is just holed and the water gone off

The most interesting item in this letter is the particulars of the atmospheric engine at Owen Vain, whence, assuming that the figure given, viz., 38 fathoms, is meant for the lift, we deduce the fact that the comparative performance or "duty" of the engine was 10,878,000 lb. of water raised 1 foot high per bushel, or assuming the bushel of coals to weigh 94 lb. (the usual assumption), then the duty was 12,960,000 ft. lb. per cwt. (112 lb.), a figure which compares very favourably with engines that Smeaton, for example, had built. Watt's statement that the engine was "not a very good one" can hardly refer to its performance, therefore.

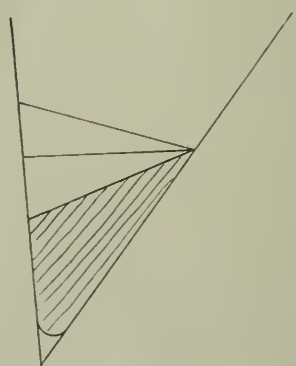
The letter shows also that the charges that Watt proposed to make for their new engine were not yet settled, but that Watt was at this moment in favour of making a charge per cubic foot of water raised to a certain height.

Boiler-Gauges and Piston-Packing.—The next excerpt [Boulton MS.], again from a letter to Boulton, is from Redruth, September 12th 1778. Watt tells about his troubles and his wants, and asks Boulton to come to Cornwall if he can spare time :—

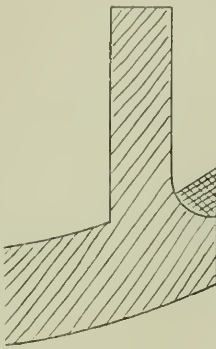
——At Wheal Union yesterday I found the Engine going very well. It had forked the first lift, 10 fath^{ms}, on Thursday morning and was working in fork to bleed the country, which was 10 strokes p^r minute. They had gradualy found steam more & more easily, & had then the damper almost shut. As to the burning of coals nothing could be known with certainty but that it diminished——

Dudley had done almost nothing to the steam cap and was at Hallamanin where they have just got the Cylinder on end & have received account of the Soho goods being at Hayle—— On Thursday evening Mr. Bonze called at the Engine in his way to the monthly meeting or account at Marazion. He praised the going of the Engine and said it was better than those he had seen of ours in y^e north, he paid up his costs & signed his absolute renunciation of

his Dole in fav^r of the Company. His reason for this is s^d to be partly pique and partly that he is rich, has no family, and despairs of more Engine business—— If you can conveniently leave your business, the sooner you arrive here the better—But please remember the following commissions—— Cause call upon Coulson for Hall piston rod & send it—— Bring with you from Pinnick 4, 2 inch valves same as he made for us last 4, 1½ [inch] valves same kind and 4 of his 1¼ inch common sort. If he cannot gett them with solid bridges ready in time for you bring one common 2 inch, 2, 1½ common & y^e 4, 1¼ inch ones bring also as many Glass tubes one fifth inch dia^r as will make a dozen boiler guages 14 inches long each they can be apply^d exceeding conveniently, you may bring also 4, ¾ valves they will have their use——please also bring a pound 12/ green Tea & a pound 8/ souchong—— For Mr Scott a 24 will be sufficient but Cylinder should be made for y^e comm^n stroke so that by putting in smaller working barrels deficinces may be supplyed if any arise—— I shall so soon as in my power send plans but insist that nothing be ordered till then as I have improvements to make especialy in y^e piston—— As to Richmond people I would put y^e Engine in order & gett some good Engine man to attend it for a week or two & then if they will not pay sue them—— It is nonsense for us to plague ourselves with any more small engines unless where the common Engine is understood & prejudice is on our side—— These people are a knot of complete Blockheads and if you can once gett your money I would never go near them more—— I had discovered all you mention in relation to piston leads before I got yours; but imprimis a mixture of Lead & tin is much worse than lead for its melting point being abt 300^d it grows so soft as to tear itself in pieces by y^e heat which lead does not do so badly—— 2dly the too great inclination of y^e cones is true but its effect may be lessened by the slope of y^e upper side no pasteboard should be put under y^e leads but laid upon the bare



cone—— They may be cast in long slips of copper with 1 oz tin to pound and afterwards bent to lay in place—— The new piston I propose is of this fashion



for here the roping will come always into a narrower & narrower place and by virtue of y^e semi elliptical figure will end at right angles to cylinder and have no inclination to sink in y^e oackum though no lead were used but I think it will be best to have a small slip about ½ inch, which will [be] pressed by the oackum in proportion to its upper slope. The oackum & roping should be quite white i.e. free from any tarr & then very little Grease is necessary, for y^e article cannot be afforded particularly here where y^e Engine men eat it Adieu—— Upper leads of piston should be short and deep

The Mr. Bonze mentioned was one of the Cornish engineers who opposed the introduction of the Watt engine, but was honest enough eventually, as this letter shows, to acknowledge its superiority.

The reference to glass tubes for boiler gauges must be for water level indicators, and shows how early this safeguard was adopted. The most important part of the letter, however, is that referring to the different designs for metallic piston packing and to the trials of them. The incidental touches—one about the price of tea at that time and the other about the predilection of Cornish engine men for tallow—will be appreciated.

Letter Copying.—The next excerpt [Boulton MS.] is from a letter addressed to Captain James Keir, and in it Watt gives his recipe for making copying ink for use in the letter-copying process which

he had patented in 1780, and to exploit which a subsidiary company —James Watt and Co.—had been formed. Of this firm Captain Keir * was partner and commercial manager :—

Cosgarne Jan^{y} 15th 1782

Mr. Keir

Dear Sir,

I received yours by Mr. Henderson, as I have no opportunity at present for making experiments I can only give you my thoughts on Ink making which if you will please to revise and try we may afterwards agree upon a receipt. To make half a pint of Copying Ink, take one oz troy of the best Aleppo Galls, put them whole into 1 pint of clear water, taking care that the said water be perfectly free from Lime Chalk or any other Calcarious or alkaline matter; put the Galls and water to boil in a tinned Copper, or in a Glass vessel, make it boil moderately quick untill you judge that you have about half a pint or a little more of the liquid remaining and the Galls are become quite soft, which should happen in about an hours boiling. Strain it through a cloth, and if less in quantity than half a pint, add warm water to make it up, if more in quantity put the liquid on the fire again but without the galls and boil away so much as will reduce it to that quantity, when cold add to it 1½ drams of Gum Arabic in powder, shake it or stir it frequently untill the Gum be dissolved. Then add of the best Green Copperas 2 Drams and of allum 1 scruple or 20 Grains, shake or stirr it frequently and when the salts are dissolved it will be fitt for use But will be pale, to remedy which defect, suffer it to stand in an open Glass tumbler or some such vessel for 48 hours, & then pour the thin part into a bottle to be kept Close corkd for use—— To prevent moulding put to the ½ pint ½ a dram of Cloves in coarse powder

If upon trial the ink after being carefully made according to the above directions does not yield a good Copy or does not yield a Copy after it has been written 24 hours, there must be added to the ½ pint 3 or at most 4 drops of concentrated vitriolic acid which will make it write pale & thin & copy at a longer date But those who can obtain the acid of Tartar that is the acid extracted from Tartar may in place of the vitriolic acid add 2 or 3 Grains of the dry acid of Tartar which produces a still better effect than the vitriolic acid.

Watt then goes on to give results of other experiments in making copying ink, as a guide to Captain Keir. If Watt was not the discoverer of the property of adding gum or saccharine

* An account of this remarkable man will be found in Prosser—*Birmingham Inventors and Inventions*, 1881, page 20.

matter to tannin writing ink to enable it to "set off" on damp transparent unsized paper, he was the first to apply the fact usefully and to work out a commercial application in his roller copying press. It should be noted that this press was designed for copying single sheets. The letter copying book and the screw press were introduced later, but it may be here remarked that modern office copying methods have reverted to Watt's original idea.

Quite a large business was done in the roller presses with all parts of the world; a few have been preserved, notably in the Science Museum, South Kensington, and in the Watt Museum, Birmingham. As showing the prejudice which the innovation caused, banks and other institutions agitated for its suppression, fearing that it would encourage forgery! It is difficult to imagine how the world would wag nowadays, especially the commercial one, without means of copying documents rapidly.

Iron Cement.—The next letter [Boulton MS.] to be quoted from is to Boulton from Cosgarne, Cornwall, dated April 10th 1782, and is interesting as fixing an early date for the experiments that led to the invention of the well-known iron cement (iron borings, sal-ammoniac and sulphur), which has been so useful to engineers :—

—— am trying some experiments on a new cement for Joints, as I have lost faith in putty which always fails in the long run in all the vacuum Joints owing to the repeated exhaustions and repletions, I have several sorts in view one, a fine powder of Iron in a metallic state mixed with substances which may dispose it to rust and some mucilaginous matter which may give it elasticity and keep it in place till it rusts, and a new substance which is neither soluble in $\bigtriangledown$ [i.e. water] $\sqrt[s]{}$ [i.e. acids] nor Oils but can be softened by water to the consistence of Caoutchou & which when mixed with earthy substances becomes as hard as stone, and can be had cheap, being the product of an English vegetable. What continued heat may do to it experience must determine. In other respects it would make a hole of an inch wide quite tight in one minute after applied and adheres to any dry substance most viciously. Caustic alcalies or acids destroy it or weaken it.

Cort's "Grand Secret" for making Iron.—The next excerpt [Boulton MS.], again from a letter to Boulton in Cornwall from

Watt in Birmingham, under date December 14th 1782, contains an interesting piece of contemporary history:—

. . . . we had a visit today from a Mr. Cort of Gosport who says he has a forge there and has found out some grand secret in the making of Iron, by which he can make double the quantity at the same expense and in the same time as usual. He says he wants some kind of Engine but could not tell what, wants some of us to call on him, and says he has had some correspondence with you on the subject. He seems a simple good natured man but not very knowing. He says he does most of the smith work for the King's yard and has a forge a rolling and slitting mill. I think him a brother projector—& have therefore put him off untill some of us can view the ground which he readily agreed to as he has water for most of the year. . . .

Cort, who is mentioned here as the inventor of "some grand secret in the making of Iron," was the unfortunate Henry Cort, the inventor of the process of puddling for the production of wrought iron, the patent for which was granted to him two years later. Probably the "secret" referred to is the iron rolling mill for which Cort took out a patent in the following year, and for which he would naturally want an engine. It was to obtain more capital in connexion with his inventions that he entered into his unfortunate partnership with Adam Jellicoe, which led to his ruin. The kindly reference to him as a "brother projector" shows a fine trait in Watt's character.

Steam-Turbine.—The next letter [Boulton MS.] is again to Boulton, and is actually upon the subject of the steam-turbine. Most engineers will be surprised to find that it received practical and theoretical attention at such an early date as this, and their surprise will be increased when they learn that it was not lack of ideas that delayed its advent, as a search of our patent records will prove. In fact, the position of the steam-turbine was for nearly a century that in which the gas-turbine is to-day.

Birmingham

Mr. Boulton May 11th 1784.

Dear Sir

Yesterday I heard from Dr. Priestley that Kempelen's engine is a

Barkers mill turning in the air by the force of steam, which is very different from my former idea of it, & perhaps a worse thing for him.

Before we say much about its merits it will be best that he should specify lest by talking about it we put him on improvements; for it is capable of them.

I apprehend that the power is to be calculated in the following manner. Suppose the steam = to 30 inches mercury & the sum of the orifices = 1 sqr inch, then the propelling force will be 14 lb pr inch when the machine is at rest, & as the velocity of stm issuing under said pressure is = 1800 feet pr ″ [i.e. second] & this machine is subject to the laws of undershot mills, the proper velocity for it is $\frac{1}{3}$ of ye above i.e. 600 feet pr ″ & ye effect will also be about $\frac{2}{3}$ of the power or 10 lb × 600 = 6000 lb 1 foot high pr second. The quantity of steam employed will be 1800 ÷ 144 = 12·5 cubic feet steam. Now in one of our Engines 12½ cubic feet steam would raise 250 feet ▽ [i.e. water] to 10 feet high = to 15512 lb 1 foot high. This then would be the effect of the machine working in vacuo, compared with our engine, but by another theory it comes out that the effect might in that case be greater but this second theory is so complicated that I cannot say I understand it thoroughly, nor do I think there is occasion because 600 feet pr second seems to me an impossible velocity on account of the necessary friction of the machine I should suppose 100 feet pr second to be a maximum in that point, then the effect would be = 14 lb × 100 feet = 1400 lb 1 foot high pr second by the same expense of steam viz 12·5 cubic feet.

But as he uses no vacuum & cannot without interfering with us If he makes Steam = to 30 inches mercury, its density will be 900 & the velocity pr ″ will be 1290 feet The proper velocity 430 feet pr second, ye effect 4300, & the quantity of steam 18 cubic feet because it is of double atmosphere density: He will find great difficulty in making boilers of any tolerable size which will be steam tight. This latter engine would be = to about 7 horses & would require a boiler $\frac{2}{3}$ as large as that at Chacewater, and in the case of 100 feet pr second velocity working in vacuo.

The machine would be equall to 2½ horses, & would require a boiler = to ye evaporating 26 cubic feet water pr hour = to that of a 38 inch cylinder Such a boiler would cost almost as much money as one of the engines which was of that power. but you will remember that if a velocity of 600 feet pr ″ be possible that the Kempelen working in vacuo would be = to 11 horses & the 38 inch cylr is = to 27 horses. So that you see the whole success of the machine depends on the possibility of prodigious velocities. The collar through which the steam is transmitted will have much friction, but that might be obviated in a great degree by making it turn in a collar of mercury which however if he has not thought of you will take care not to mention. As he has a very complete model of it ready made you may try on it what

quantity of coals are burnt, ▽ [i.e. water] evaporated and work done, also if you can the density of the steam, but dont propose a steam guage if he has none. The fairest way of trying the power will be by pumping water or by raising a weight. In short without god makes it possible for things to move 1000 feet p^r '' it can not do much harm.

The apparatus under discussion is really only our old friend the æolipile which had been schemed by Hero of Alexandria 50 A.D. at least. The apparatus in question was patented (No. 1426) April 11th 1784, by Wolfgang, Baron von Kempelen of Presburg in Hungary, who is best known as the inventor of an automaton chess-player. Very naturally, it was submitted to Watt, who then goes into the question, and basing his reasoning on the velocity of steam (his figure, by the way, must have been observed by himself, and is wonderfully near the more exact determinations of later times), concludes that such a high speed of revolution is necessary as to be, in the then state of the arts, impracticable. Watt feels, therefore, that the apparatus will not become a competitor with his engine. Nevertheless, his fertile brain cannot be prevented from throwing out a suggestion for improving the apparatus, which, however, he desires shall not be disclosed to the patentee for fear of adding to the value of the invention.

Mistakes in Drawings.—The next letter to be given [Boulton MS.] was written to Matthew Boulton, who was at Chacewater in Cornwall. It is typical of dozens:—

Birm^m. Nov^r 5^th 1785.

Mr. Boulton

Dear Sir,

I have yours of the 31^st. I am exceedingly sorry to find that you are still kept so much in the dark concerning, the answer of Mr Bedfords agent, of which I have yet received no intelligence but hope that Mr Garbet has before now advised you, and that there is no necessity for your coming away before the time you mention.

I am exceedingly vexed at the omission of marking the distance of the centre of the perpendicular radius of Wheal Fortune below the horisontal line of the centre of Gudgeon it should have been markt 42 inches, the perpendicular link being $\frac{1}{8}$ inch shortned by the angle it makes.

It is drawn right in the General section which I wish had been consulted, and indeed in new subjects of that kind which are so complicated, it should be a rule to make some kind of rough model to see that it is right as mistakes may be fallen into by any body

At the time that and other drawings were dispatched my head was so confused with various matters that the omission passed unnoticed, and in general in new and intricate contrivances it requires more attention and genius to obviate every difficulty than I am possessed of, especialy where there is no *candid* reviewer to come after me & point out what seems to be mistakes. such good office is hardly to be expected from those who consider their own inventions as better than mine, and may think themselves crampt by having any rules laid down to them to work by. such men are more likely to enjoy the gratification of their vanity in detecting one in error (which it is next to impossible that the man who projects upon paper, can intirely avoid) then to contribute any assistance in supplying the defects which may occur. This evil is augmented by my inability to lay down these drawings with my own hands as I used to do, consequently errors may escape me in a cursory looking over a drawing which would not have done so if it had been the work of my own hands.

On the whole I find it now full time to cease attempting to invent new things, or to attempt anything which is attended with any risk of not succeeding, or of creating trouble in the execution. Let us go on executing the things we understand and leave the rest to younger men, who have neither money nor character to lose.

The length of the regulating radius as markt is right as you will find on altering the centre.

say, Length from Centre [?] Beam gudgeon to centre gudgeon at top of perpendicular links $\overset{\text{feet}}{15}$: $\overset{\text{in.}}{3}$: $\overset{\text{10th}}{2}$ perp^{r} links $42\frac{1}{8}$ inches Centre of D^{o} below Horizontal line 42 inches, from centre piston rod 28 inches Length of regulating radius 9 feet 5 inches between centres Centre of piston rod from Centre gudgeon 15 feet——

As to the paragraph you mention, I suppose it was put in by some wiseacre or more probably by the millers, as the building has never reeled a iota, but as it has no walls & consists merely of floor posts set upon one another, the props you mention were put up on *all* sides to *prevent* reeling. all the work at the mill seems extremely well done, the only thing wrong seen hitherto is expence which I fear will be very great

I had no london news of any importance or would have wrote to you, nothing indeed but what may be safely reserved till we meet. The Engines we have erected are all doing very well & Felix Calvert has bespoken one which he is to cause to outdo Whitbreads in magnificence. We have also got another small order for a 4 horse engine for Nottingham.

I cannot easily answer your letter by the London p[ost] as it goes out at 4 and now we seldom receive the letters till near one which is too short an interval, besides by the instance of mine of the 27th it seems only to save one day—— I am glad to hear that C.water [i.e. Chacewater] is like to stop drawing money from us, though it should do no better, and also that the £1700 is brought to account.

I have been ill for a week with a kind of a flux which I think has now stopt, but I am low & have got a headache tonight. I shall be very happy to see you safe home but cannot help acquiescing in the propriety of your stay, the late instance has shewn the necessity of it

Wishing you health & good luck, I remain affect^{ly}

Yours James Watt

In this letter Watt is much worried over a mistake which had gone undetected in the drawings, because he has now had to entrust the draughtsman's work to other hands. This shows how drawing office practice grew up. It is soothing to have Watt's dictum that "it is next to impossible that the man who projects upon paper can intirely avoid mistakes," for which of us have not made such mistakes?

Testing of Materials.—The next two letters [Boulton MS.] should be read together, as they are both upon the same subject—a mysterious fracture of iron, about the quality of which there was in consequence considerable difference of opinion :—

Birm^{m} Mar 20th [1786]

Mr. Boulton

Dear Sir,

I wrote you yesterday, since w^{ch} have received a piece of F. Scotts gudgeon w^{ch} is a curiosity being the largest cristallization I ever saw. They call it very bad Iron & want us to pay the damages w^{ch} I cannot consent to as we did not make it & had no profit on it. It was made at Bersham besides I am not yet satisfied until I make some trial of it that the Iron is so bad as they call it some time ago they lett something fall into the fly pit which prising the fly up broke off the upper plummer block of Gudgeon & very probably at the same time broke this part of Gudgeon, for one fracture is worn smooth, had the Gudgeon been very bad Iron it would then have broke at the neck—— I have almost always observed the thick barrs of the best Swedish break with a grain resembling this, and I believe most thick lumps of Iron that are sound welded assume a cristallization. It

may have been hurt by punching out the cutter hole hot. I w^{d} there^{re} recommend to drill & chisel out this hole in the new one, I shall write to him tomorrow not being able today, having had Mr. S [i.e. Symington] senior with me all day on L[ead] Hills business, & I shall break the Iron in another place till that is done I cannot say it is not cold short shall however write W^{n} [i.e. Wilkinson] & Bersham upon it & stop any more Gudgeons being made there.

Yours &c. James Watt

Mar 22^{d} 1786

Mr. Boulton

Dear Sir

Yesterday I crept out to Soho & tried the Iron of F. Scotts Gudgeon, when laid with the angular side  downwards between two supports about 5 inches asunder we could not break it until it was notched cold on the ridge pretty deep & after notching it stood many severe blows from one of our strongest men with a hammer of near 40^{lb} weight before it broke but when it broke it was all at once & shewed the same chrystallized grain as in y^{e} org^{l} [i.e. original] fractures.

I then splitt a piece of the Edge of it & caused draw it out into a rod of ½ inch square and abt 12 inch long this rod bore being quite bent double in the middle, but broke in attempting to straighten it again. I then gave one of the pieces a slight notch & put it in the vice, it broke quite short without bending, & showed a cold short grain I served the other end the same way & it bent somewhat before it broke & shewed some tough & a smaller grain.

In the opinion of our Smiths a barr of good comm^{n} Swedish w^{d} have broke as easily (though of same size) as this did in the mass, though it w^{d} probably have been tougher in the small piece. On the whole it does not appear that the Iron was remarkably bad, but such accidents as broke the fly & tore up the plummer blocks w^{d} demolish almost any hard Iron & soft Iron is not fitt for Gudgeons. I know not what country Iron it is but W^{n} [i.e. Wilkinson] used to get his Iron for Bersham from Cumberland Charcoal Iron throughout. In our shops we work nothing but the best Swedish we can buy which has cost us lately 19/6 p^{r} cwt. If you c^{d} hear of any Spanish Iron cheap I will send proper sizes & I think we c^{d} apply it usefully. As far as human foresight can extend we sh^{d} not expose ourselves to such accidents if can be prevented. I have totaly forbid the making any more Iron work at Bersham. I have kept all the specimens of this Gudgeon for Mr W^{s} inspection & to stay his stomach in the meantime have treated him with

a letter on that & on his Boiler plates but have yet said nothing of the accident which I believe broke the Gudgeon, as he is too ready to catch hold of any excuse

Albion Flour Mills.—The next letter [Boulton MS.] to be quoted, dated Birmingham, April 17th 1786, is about the Albion Flour Mills, for that period a very large undertaking, being the first application of the steam-engine to grinding corn and the first example of the double-acting rotative steam-engine in London. In fact it was intended by Boulton as an advertisement for the engine. He and Watt were the largest shareholders in the undertaking and were naturally anxious to "unload" so as to reduce their liability. Nothing can exceed the insight into Watt's character that this letter gives.

It has given me the *utmost* pain to hear of the many persons who have been admitted into the Albion Mill merely as an Object of Curiosity—— Were there no other loss than the taking up your time it is a very serious one but there are other essential ones which are too obvious to need to be pointed out, among which are that the disgraceful condition in which it has hitherto been has been more likely to do us hurt than good as engineers & the bad management or want of management in other [?] respects must hurt the credit of the Company—— I hear from different quarters enough to convince me that we are looked upon by the serious common sense man as vain and rash *adventurers* that our talking of what we can do is construed into either a want of ability to perform it or the foolish cry of Roast beef *—my natural hatred of ostentation may perhaps make me feel these things too strongly, but surely those who say so think they have some reason for the observations & it cannot happen that the most pointed of them can come to my ears, considering how little company I keep—— Among other things I heard some time ago that on a certain day there was to be a Masquerade at the A M, and this from persons no ways connected with us & who had heard it as com^n^ Birm^m^ talk—and I felt it as a severe reproach considering that we are much envied at any rate, everything which contributes to render us conspicuous should be avoided, let us be content with *doing*. R. [i.e. John Rennie] no doubt has vanity to indulge as well as us but he sh^d^ be curbed & the bad consequences pointed out to him, it will ruin him, Dukes & Lords & noble peers will not be his best customers—— And let me entreat that the doors of the Mill be strictly shut against all comers without an order signed by three

* *i.e.* the announcement of one's good fortune.

Comittee men & that only at a comittee meeting on some fixt day of the week & let that rule be inflexibly adhered to. I know that you have been actuated by good motives in showing the mill, namely the desire of getting quit of part of the property we have in it & the hopes of making interest to get a charter, but I conceive these things will be better attained by making it a mystery to the many & by the external appearance of business.

I cannot think on corn machines till every thing else is successful—— In the meantime the corn sh[d] be frequently turned & the flour attended to, for it will suffer much more than the corn.

I remain My Dear Sir
Affectionately Yours
James Watt

The Albion Mills were situated on the south bank of the Thames in Southwark, and being in a commanding position the undertaking excited, as the letter leads one to infer, great interest. It is enough to say here that, in March 1791, after a long period of opposition and worry, just when the undertaking bid fair to prove a success, the mill was completely destroyed by incendiarism. The loss fell heavily on Watt, but heavier still on Boulton; nevertheless, the mill had served one of its purposes—that is, that of drawing attention to the new engine as a prime mover for millwork.

Application for Engine Monopoly in France.—The next letter [Tangye MS.] is of formidable length; it is dated February 10th 1787, and was written by Watt on behalf of the firm to the Abbé de Calonne, brother to one of the last Ministers of Louis XVI. M. de Calonne filled, at the moment, the office of Controller-General of Finance. The object of the letter was to appeal to the Abbé, as a friend at court, to procure an *arrêt de conseil*—equivalent to letters patent—for Watt's rotative engine. The monopoly of the pumping engine had been obtained earlier, but the French engineer, Perier, who is so frequently mentioned in the letter, had evaded it so that Watt and his partner were anxious to get a new monopoly to include the recently invented rotative engine, and yet prevent Perier from too large a participation in it. While no doubt a large part of the letter was due to Boulton, who was, of the two, decidedly the diplomatist, yet we must credit to Watt an equal share in the breadth of view displayed and in the business acumen shown.

Feb 10th 1787

Monsieur l'Abbe Colonne,

My Dear Sir,

You will perhaps accuse us of neglect in not writing to you sooner, we have not however, in any degree forgot you, the friendship with which you honoured us, nor the many good offices you did us, and the civilities you so obligingly conferred upon us. In few words, the manly, candid, and open manner in which you behaved toward us have made an indelible impression on our minds.

We send enclosed, or with this, an abstract of our sentiments concerning the Canal of Picardy, which we beg you will do us the honour to lay before the Controleur General, and make our excuse for not writing him personally, as we cannot do it in French, and would wish to take up no part of his time unnecessarily. From every view we have been able to take of that subject, we conceive it to be a very great national object, which should be executed coute qui coute, both as a thing most extremely useful in itself, and as an object which can scarcely fail to reflect honour on all concerned, if not prevented by some unforeseen circumstance. The advantages to internal commerce will probably be more than anybody has yet pretended to predict.

We also send with this letter No. 1 a representation of our case in respect of the arrêt du conseil which was read to Monsigneur le controleur General and De Vergennes by Mr. Genet while we were at Paris and then met with their approbation, you know the reasons why we did not then follow up their favourable sentiments, they were the fear of engaging Ministry in the disagreeable business of procuring the unregistering of the arret, and a sincere desire of doing no injury to Mr. Perier, which we could avoid, whom at the same time we could not from his former behaviour place that confidence in, which some *traits* in his character would otherwise have inclined us to do.

No. 2 contains what we meant for the substance of a requête au conseil for a fresh arrêt, and as we intended it to form the recital of the causes for granting the arrêt, we have added a more correct specification of our invention than was contained in the former arrêt. Mons. Abeille, Inspecteur general de Manufactures Rue de la Feuillade promised to reduce it into the proper form of a Requête, whenever you should put it into his hands, and also to draw up the arrêt in due form if the requête should be granted.

No. 3 is the copy of the old arrêt.

The use of No. 1 is to bring before you some short hints of the facts on which our pretensions are founded, but we should think it improper to enter into them so fully in the recital of the arrêt which being a public instrument should be so calculated as neither to give offence in France or England, and in the latter account all newspaper publications concerning us ought to be

forbidden, as however honestly as we may act in regard to this country, there will be wanting those who will industriously seek out every occasion of exciting jealousies concerning us, and we have already met with several who have thought we have spoken too favourably of France in telling what we think the truth as to the views of our ministry in making the late treaty of commerce, in which they will have it our ministry have not been sufficiently tenacious of the interests of this nation, as you will no doubt see by the English newspapers.

You know that in the last conversation we had with Mr. Perier it was proposed by him that the arrêt should be passed in the names of Boulton and Watt, and Perier freres, that the benefits arising from the exclusive privelege should be divided into two equal parts, one to B. & W. and one P. F. thus Mr. P. should take upon them the rearrangement of the business in France, and B. & W. in England. That we should from time to time furnish such new plans, drawings and directions as would be wanted. That all new improvements and all hitherto made by either of the parties should be in common to the concern, that Mr. P. should allow B. & W. 5 °/ₒ on all materials furnished by them, and that B. & W. should do the same to Mr. P. in respect to any they should furnish. On the part of B. & W. I made the following proposal (which you know was what we intended before we talked with Mr. Perier on the subject).

That the arrêt should be requested in the name of B. & W., That B. & W. should grant to Messrs Perier their license to make such kinds of engines as they have hitherto made, tho' included in the exclusive privelege granted to B. & W. That Messrs P. should not make any other sorts of these engines than what they have already practised or publicly made prior to the said conversation, i.e. that all improvements already made by B. & W. which Messrs. P. have not yet, or had not then practised, or which B. & W. shall invent in future should be the sole property of B. & W. and in like manner that all improvements or new inventions that shall be hereafter or publicly specified shall be the sole property of Messrs. P. That in order to prevent any disputes concerning the property of any new improvements on the engines, we shall give in a specification of all our new inventions which we have already practised, or which we judge to be useful, and which we do not mean to permit Messrs. P. to use.

That both parties should mutually consult together on the terms on which they should serve the public, and should be as much as human nature permits de bonne foi in not interfering with each others customers.

That each party should be at liberty to manufacture their own materials or purchase them where they chused or found it most for their advantage. That the license to be granted by Mes. B. & W. to Messrs. P. shall only be confined to themselves, and shall not be transferable to others.

That we wish in no way to cramp, or confine Messrs. P. or other in making or improving the ancient machines, provided they do not use our principles contained in general specification.

We agreed with Mr. P. to take no step in procuring patent without his knowledge, but took time to consider which of the two propositions we should adopt, as he was to consider them on his part. After consideration, we can only offer the last proposition, viz. that made by us, and that for several considerations, 1mo because our [sic] affairs would in the case of a partnership, in the profits of the invention be entirely in Mr. P's power, 2nd because he would *naturally* supply as many of the materials as possible from his own manufacturing, and probably at prices which would bear hard on our customers, and lessen the profits properly due to the invention. 3rd. because he would and must be the ostensible man and in case of any rupture he only would know the minuteæ of the business and be acquainted with our customers. 4th. because we found he had more enemies than friends, perhaps very undeservedly and they would become ours on account of the [illegible] and our friends would be less attached on account of the effects of monopoly, or engrossing the whole business of the kingdom by one company, which would make many endeavours to burst the fetters, and we might become as odious as the Compagnie des Eaux, and a patriotic minister might labour to find an Yvette to balance us. 5th. because however we might agree about the division of the money we should never agree about the division of *la Gloire*. Mr. Pr. s'est montré tres *avide* du Gloire d'autrui, et nous sommes tres *tenaces* de notre propre gloire, et jalouse de celle d'autrui. What faith can we put in a man who has (to put the best construction) at least *permitted* our invention to be called his, who has said that the drawings we furnished him with were intended to mislead and that if he had built the engine according to these drawings, it never would have answered, and yet did build the engine according to these drawings, and with the materials sent by us, and it has answered? He has indeed made some small deviations but not for the better. What security can we have that he will not do so again, and that all the faults of the engines will not be called ours, and the virtues Mr. P's. There being no guarding these points, we esteem it better to meet him in the field of honour as a fair opponent than to compromise our own honour and that of our friends by a bargain derogatory to it, and probably offensive to the public.

To entertain sentiments of revenge is unmanly after receiving and returning civilities, but to *forget* injuries and to expose ourselves to a repetition of them is imprudent.

We cannot conceive ourselves as called upon to make the elogium of Mr. P. but it would be dishonourable to deny that we think him a man of great abilities, who executes his work well (say in a masterly manner) and

that he is possessed of much good sense and judgement, and of a great fund of knowledge in his profession with the manners of a gentleman.

We are sensible that we forgo a great deal in not availing ourselves of his abilities and local knowledge, but we prefer peace and good fame to money. France is big enough for him, and us both, and we trust that his good sense and feelings of honour will prevent any disagreeable interferences in the course of business, and we shall on our part do our endeavours to avoid interfering with him.

We have therefore, taken our line, and we hope Mr. P. will see his advantage in agreeing to the terms we offer, which we think just, otherwise, we would not endeavour to impose them on him, On our part we suppress our feelings on all that has past, we give up quietly that part of our property which he has got into his possession, and which he now calls his, *upon condition that he will rob us of no more*, and that we may be permitted use of such things as he borrowed from us, as freely as we permit him to do. We do more. If a privelege is granted to us, we protect Mr. P. from all opponents but ourselves, and those acting for or under us. We require nothing of him except that he will not either directly nor indirectly oppose a privelege already granted to us by government from being prolonged and put in force.

If Mr. P. will not agree to these terms, we must try our force in attempting to get a privelege without having any further considerations for his interests, or, perhaps without meddling with Engines, in [illegible words] him and troublesome opposition, though a fair [illegible words] more tender points. If government do not desire to grant our request in point of this privelege, and *in making it become effectual* we will say, that they ought to reward us in some other way, for the services we have done upon the faith of the former arret, and we believe with a minister so just, generous, and candid, as Mr. De Calonne we shall have no reasons to complain.

In short, we trust in a continuance of that Bon adieu liberality and candour we met with at Paris, so long as we shall merit it, but above all we rely upon your friendship, and that of Mr. de Sainte, for the bringing of this matter to a conclusion.

Everybody of observation here, speaks with admiration and applause of the regulations which Mr. le Controleur General means to propose to the assembly of the notables, and express a wish that our minister would follow the same great line in simplifying our taxes . . . . . but that part of our patriots who are not over liberal fear that he will by freeing your commerce and agriculture from its shackles make France too rich and too great for the welfare of Britain and its trade. We argue otherwise for we say that if these measures contribute to increase your manufactures or commerce, that our government will be obliged to lay aside the erronous part of their system,

and free our manufactures from their grievances, and that the richer France becomes, the better customer she can be to Britain, and that at the worst if no change of system is adopted here, and our trade becomes ruined by the agrandizement of yours, that you will have made France so desirable a country that all active men who are not rooted to the soil, like so many vegetables, will remove thither, and help to make it still greater, leaving our tyrannical land-holders to pay the national debt, to eat their own corn, and muddle their undertaking with their own ale, without one enlivening drop of burgundy, except what the wool of their sheep can purchase. We hope however that both nations will be wise enough to profit by each others good examples, and to pursue them with the same eagerness they have hitherto done each others follies, and that both will have reason to rejoice in the benefits of the commerce produced by the present treaty, which so many at present oppose in this country.

Mons. de Calonne did us the honour to say at our last interview [*two lines missing here*] "If their minister is so too, there will be perpetual peace between France and England, and no nation in Europe will dare to go to war with another." We repeated these words to Mr. Pitt to which he answered "that would be a most desirable and most glorious thing, *if* such are their real sentiments." You see, they both rest on the "if." In my opinion they were both sincere but which of them can answer for a change of sentiment from future contingencies, or for the action of their successors. In the meantime, they are in the right road, and I believe both nations most sincerely join them in praying that the said perpetual peace, but our countrymen fear yours are not sincere, and probably yours have the same fears, a continuance of peace, and social intercourse will in the end remove these jealousies. In the meantime, let us use our endeavours within the small circle we revolve in to rub off some of the asperities.

I send you a small treatise on the subject of taxation—which I composed about two years ago, in a fit of rage at the imposition of several new taxes on manufactures; but which I have reason to believe was productive of no good effects, so infatuated is our government in their endeavours to kill the hen which lays the golden eggs, and so tenacious are our landed gentlemen *of what they call property*, reckoning us poor mechanics no better than the slaves who cultivate their vineyards, fortunately however, they leave a country and age [*portion of letter missing*] live upon you, but you cannot have your luxuries without our help.

When I look back on the state of intoxication in which we were kept at Paris by the very flattering civilities and attentions and unmerited praise we received and the good wine we drank, I fear we were guilty of many rudenesses and incivilities, and said and did many improper things. If therefore you feel we have done so in your presence, or towards you we

entreat you to forgive us, to believe they proceeded from no want of regard or respect to those who honoured us with their company, and to make our excuse to any we have offended.

We hope to have the satisfaction of seeing you and Mr. Brunel here when the season of flowers arrives, and you may depend on our endeavours to make your stay agreeable.

Begging the favour of you to present our most respectful and grateful compliments to Mons. le Controleur General, and to believe me to remain, with the greatest esteem and respect

my Dear Sir,

Your most obliged

and most obednt. and humble servant

James Watt.

(for Mr. Boulton & self.)

As we shall not enter so much at large on the subject of Mr. P. to Mr. de St. F. I shall mark with red ink the parts of his letter, which should be in some degree an exhaustive one.

Further developments were arrested, of course, by the troublous times of the French Revolution.

John Southern.—The next letter [Southern MS.] is one addressed to John Southern, Watt's ablest and most trusted assistant. He was born at Wensley, Derbyshire, 25th January 1758, and entered the employ of Boulton and Watt when twenty-two years of age. He became a partner in the firm in 1800, and remained with them till his death, which took place at Oakhill, Handsworth, 28th July 1815. He was buried in King's Norton Church, near Birmingham, where there is a tablet to his memory. He did the indoor or drawing-office calculation and estimating work just as Murdock did the outdoor or erecting work. It will perhaps never be known how much Watt was indebted to Southern.

He was an excellent mathematician and contributed a Paper to the Royal Society in 1801 * on some experiments on friction, and another in the same year to the Philosophical Magazine † on the equilibrium of arches. In 1803, at Watt's request, he undertook

* Phil. Mag. vol. xi, page 377, and vol. xvii, page 120.

† *Loc. cit.* vol. xi, page 97.

researches on the temperature, pressure, and latent heat of steam. These were accepted for many years as the highest authority on the subject. They are printed in Robison's Mechanical Philosophy * accompanied by a series of formulæ deduced from the experiments.

Just at the moment that the letter below was written, Watt was attending at the House of Commons, where Boulton and Watt's opposition to Hornblower's Bill for the extension of the patent of the latter, and those who were associated with him, for the compound steam-engine, was coming on for hearing. As usual Watt was suffering from headache: the marvel is that a man of such feeble bodily health as he was should have accomplished as much as he did.

London Ap[l] 21[st] 1792

Dear Sir

I could not answer your letter yesterday having a very bad head ache & being obliged to attend at the lobby of the house in order to keep our friends together & to know when we come on again which is fixed for thursday next, by night I was so bad that I could not speak without very great encrease of the pain, I am better to day as to pain but much disordered

I have had no opportunity of consulting with Mr B, as he has mostly been employed seperately or else many people with us

In respect to the premium for a 50 horse for the use of a rolling mill, I will put it at £1,000 in hand at setting to work or in 4 or 5 installments with interest from that date—— Smaller engines should grow a little, which I leave to you to adjust in the present case When it is possible for us to think sedately we shall fix then for all cases, at present we are required to be more busy than ever, as our adversaries are strenthening their cause by false experiments & evidence of the same sort. On the other hand we gain friends, and have detached several from them Many Gentlemen spurn at their argument of our being rich & therefore fit objects of plunder, & say there can be no better proof of the good we have done, than their paying us £14,000 p[r] annum as they say for the 3[d] of it—— As they have brought Mr. Giddy the high sheriff of Cornwall, an Oxford boy, to prove by *fluxions* the superiority of their Engine, perhaps we shall be obliged to call upon you to come up by Thursday to face his fluxions by common sense but of this shall write you in time, we thank you for the agreable intelligence of Gregory's being set to rights—— The Albion Mill Engine No. 1 had better be reserved for another use I have in view, which it lies more convenient for

* Vol. ii, page 172.

Please tell my family I am well, at least comparatively & in tolerable spirits Just going to a meeting at the A. Mill

Please remember me to friends at Soho

I remain D[r] Sir

Yours sincerely

James Watt

The reference to the premium is in respect of rotative engines. With pumping engines it had been fixed, as we have said already, at the value of one-third of the saving in coal as compared with an atmospheric engine doing the same work. Now, with the rotative engine for millwork and industrial uses generally, the premium could not be fixed so easily, because data as to the prime mover—wind-mill, water-wheel, or horses—that would otherwise have had to be employed were usually lacking. The premium, however, was supposed to be more or less on the same basis. Hence Watt suggests £1,000; incidentally this shows the profit then to be made.

The Mr. Giddy referred to is the well-known Davies Gilbert, afterwards President of the Royal Society. That Southern should have been thought worthy to meet him in the law courts shows the esteem in which the latter was held.

Duty of Watt's Engine.—Another of Watt's letters [Southern MS.] to Southern is full of business details. It may be taken as being representative of hundreds of other letters displaying Watt's clearness of mind and neatness; hence part of it is reproduced in facsimile on page 529.

Truro Sep[r] 22[d] 1792

Dear Sir

We have yours of the 18[th] & approve of what you have done in the Bag affair, You will see by a former letter of our's that what much will turn upon is whether Weston binds for himself & the other proprietors, if not we must look to him the Mine & the Engine We have not heard from Raspe since, & as we intend to leave Cornwall next week, unless something new occur, suppose the matter may rest till we return

We observe your disposition of the men which is satisfactory. We entered into no engagement to furnish Mr Campbell with an Engine by March & do not understand that any is yet ordered by him, therefore wish you to come to some explanation with him—— Messrs R. W. Fox and Co. of Falmouth have

ordered an Engine for blowing Iron furnaces at Neath Abbey in Glamorganshire Double Engine 40 Inch Cylinder 8 feet stroke to work 10 to 12 strokes p^r^ minute, sometimes so slow as 3 or 4 strokes, Premium £120 a year We are to furnish Drawings for the whole Engine & blowing apparatus, The Castings, say the Cylinders &c. are to be done at the dale [i.e. Coalbrookdale], all pipes & small castings at their own foundery here. The hammered Iron work is all to be done here or in Wales so that all the work we have to do at Soho is the nozzles They are as usual in a violent hurry & *wish* to be at work in 6 months, we have not promised as to time & I doubt not can be ready long before the other things. The first thing wanted is drawings for the Cylinder, Piston, bottoms, cover, air pumps and its buckets, to be got ready to send to the dale, the next drawings for the house & boilers blowing cylinder &c which I have told them they cannot have untill I return home as it will need some consultation & consideration, for which I have got Data. It is proposed to work a Double blowing cylinder = to 2½ lb on the inch each way & the Engine not to be loaded to more than 8½ lb as they sometimes want a fiercer blast, than in common. They have lost 2 months & been at the expense of bringing their Agent from Wales to convince us our premium was too much, but they have not succeeded. Since we wrote you last have finished our trial at Wheal Butson as follows

36 inch Cyl^r = beam exactly 8 feet stroke
pump 9½ inch bore, Depth 50 fath. 2 feet = 9291 lb

First 12 hours burnt 22 bushels made 7560 strokes/ strokes p^r bushel 343·6 effect 25,539,100 lb to one foot high p^r bushel. N.B. The fire was out of course when begun and 12 bushels of the 22 were thrown in in the first hour.

Second 12 hours burnt 17 bushels of coals, made 7550 $\overset{\text{strokes}}{\text{effect}}$ 444 strokes p^r bushel = 33,001,632^{lb} p^r bushel to 1 foot

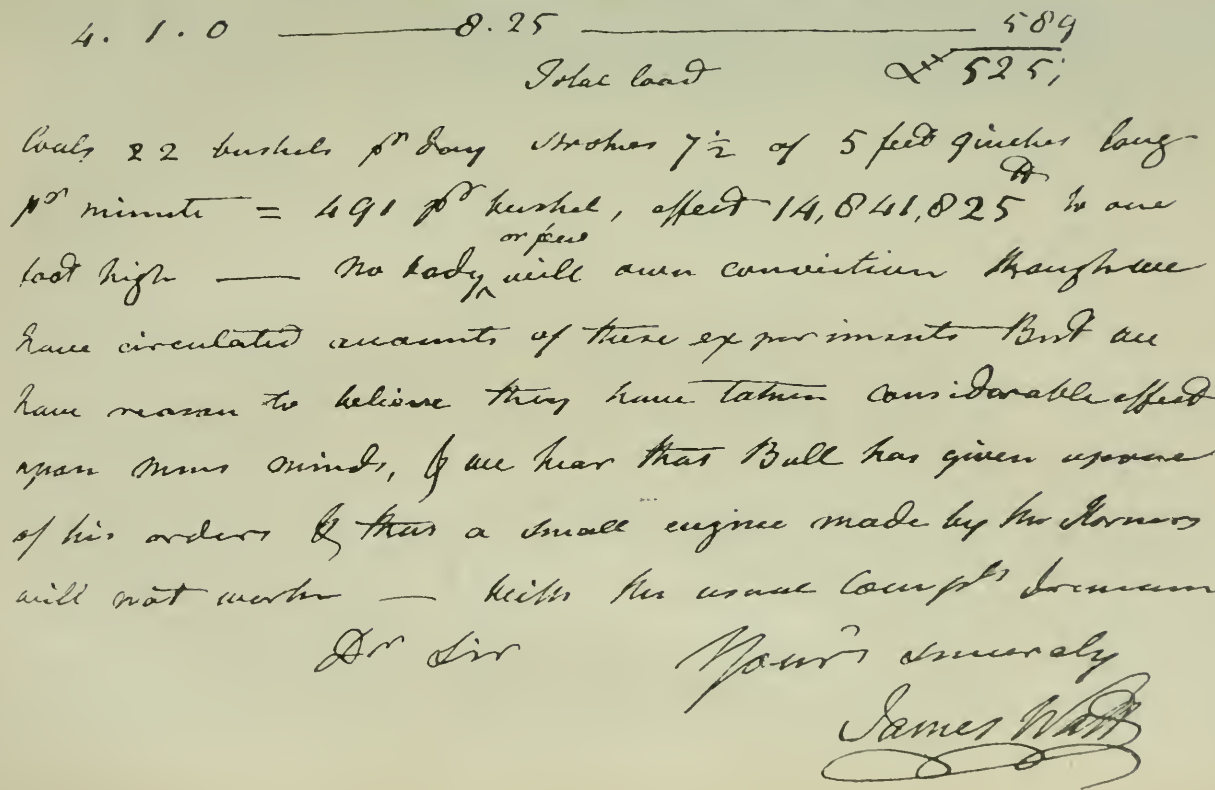
The regular effect of Poldice double 58 in the month of Aug^t is equal to 32 million, burns only 4½ bushel (100 p^r day) p^r hour for 6 strokes p^r minute Column water = 63468^{lb} stroke 9 cyl^r 6 pumps

We have been at Tin Croft the account of which for last month from the Captains is

fath			bore	lb
17	3	9	9·3	3117
10	3	3	8·5	1551
4	1	0	8·25	589
			Total load	5257

Coals 22 bushels p^r day strokes 7½ of 5 feet 9 inches long p^r minute = 491 p^r bushel, effect 14,841,825^{lb} to one foot high—— No body or few will own conviction though we have circulated accounts of these experiments. But

Portion of a letter from James Watt to Southern, 22 Sept. 1792.



4. 1. 0 —— 8.25 —— 589

Total load Lbs 525;

Coals 22 bushels pr Day Strokes 7½ of 5 feet 9 inches long pr minute = 491 pr bushel, effect 14,841,825 lb one foot high — No body or few will own conviction though we have circulated accounts of these experiments But we have reason to believe they have taken considerable effect upon mens minds, & we hear that Bull has given up some of his orders & that a small engine made by Mr Hornors will not work — [illegible] the usual Compts I remain

Dr Sir Yours sincerely

James Watt

we have reason to believe they have taken considerable effect upon mens minds, & we hear that Bull has given up one of his orders & that a small engine made by the Horners [i.e. the Hornblowers] will not work—— With the usual Compts I remain

Dr Sir

Your's sincerely

James Watt

The results of the calculations on the performance or "duty" of their engines in Cornwall, here given, are really valuable. The duty reaches to the relatively high figures of 32 and 33 million ft. lb. per bushel of coal. (N.B.—The bushel of Welsh coal was usually reckoned = 94 lb.)

Now the duty of the Newcomen engine, as established in 1778 by a committee appointed for the purpose when Watt's engine was being introduced into Cornwall, was found to be just over 7 millions, and as we have seen *ante*, the engine with all Smeaton's improvements only performed a duty of about 10 million, so that we can realize what an enormous saving Watt's engine made. Nor was this all, because when, in 1800, after 25 years of improvements, Watt retired from active participation in the business, the duty reached was as much as 55 million.

Everyone knows the progressively increasing difficulty of making further improvements, so that it would be unfair to expect the same rate of progress to have been kept up since Watt's day. Suffice it to say that high pressure and multiple expansion have enabled engineers in the intervening 115 years to increase the duty another 100 million.

The incidental mention of Raspe recalls the chequered career of a remarkable character. Rudolf Erich Raspe (1737–1794) had been in the service of the enlightened Landgrave of Hesse Cassel, but had abused his official position by abstracting valuables from the museum collections entrusted to his care. He fled eventually to England, and about 1782 gravitated to Cornwall where his mineralogical knowledge gained him a situation of assay master at Dolcoath Mine. While there he published his world-famous "Baron Munchausen's Travels." At the date of this letter the

suggestion is that Raspe was in the service of Boulton and Watt, an incident in his wayward career hitherto unrecorded.

Boulton and Watt v. *Hornblower*.—The next letter [Southern MS.], again to Southern, shows the lawsuit still dragging on its weary length :—

London 17th June 1793

Dear Sir

I have been confined to day with a headach and have yet received no account of what has passed in Westminster hall or with our lawyers & fear I shall not hear in time—— I have rec^{d} the spindle which seems right—— such quibbles as you mention form the very essence of the law, we had like to have been ruined because the patent instead J W of the City of Glasgow Merch^{t}—says simply *J. Watt* the former being in the specification & in the act, which by the by has many such kind of errors. This mighty affair they say they have a remedy for, but there is something else which I cannot comprehend that they stick at, and keep us in a horrible suspense—— Mr Wilson & his Gang are however on the road as it would have been too late to send for them when the matter was settled for trial——

Napoleon's threatened Invasion of England.—The next letter [Boulton MS.], written to Boulton after their celebrated partnership had been dissolved and both had retired from business, is quoted because it throws a sidelight on the energetic steps taken throughout Great Britain to repel Napoleon's threatened invasion, and is particularly interesting, therefore, at the present juncture :—

Glenarbuck near Glasgow
Augst 31st 1803

. . . I have wrote to James [i.e. his eldest son] who I expect is now with you to put down my name James Watt of *Heathfield* in the Handsworth list as a subscriber to the fund at Lloyds for £100 & £10 to the Handsworth parochial fund, which with what I may be called upon to do in Wales, will be fully as much as should fairly come to my share of the matter. The people here content themselves with forming corps of volunteers both Horse & foot & give themselves no trouble about subscriptions, they say the officers' pay which they give up for the purpose is sufficient to cloath the men—— I saw the Dumbartonshire Yeomanry reviewed the other day, when they made a very respectable appierance, & went through their exercise very perfectly though they had been only 8 days in training. They were mostly farmers

well used to the weather & I daresay would behave well if called into action. . . .

Gregory Watt.—The next letter [Boulton MS.], again addressed to Boulton, has a pathetic interest. Watt and his wife were accompanying their talented but consumptive son Gregory on a journey for the purpose of trying to restore him to health. They arrived eventually at Sidmouth, but becoming worse, Gregory was removed to Exeter, where he died little more than a month later, on October 8th.

As evidencing Watt's solicitude for his son, we may mention that, in conjunction with Dr. Beddoes of Bristol, he had designed and constructed for sale an apparatus for inhalation of "factitious airs" for affections of the lungs and throat, fully described in pamphlets, of which several editions are known.

Bath Sep^r^ 4^th^ 1804

My Dear Sir,

As you will have heard of Gregorys health from James & I have had nothing else to write I have not troubled you with correspondence Gregory continues free from his fever by virtue of the medecine he takes, he has gained a little strength & appetite & has good nights, neither is his cough so troublesome as it has been, but his breathlessness is not much mended & he is still very weak, we are to leave Bath on Friday for the coast of Devon, the exact place is not yet fixed but as soon as we arrive at a place of rest you shall be informed how we go on. With all these hopes of amendment we have still much anxiety about the result, but we must submit to the decrees of providence & be thankful for the relief from suffering which he has enjoyed. All the party here joins in kind remembrances & best wishes to you & your family & I remain

My Dear Sir

Your affectionate friend

James Watt

Scientific Pursuits in Old Age.—The next three letters [Southern MS.] are polite acknowledgments to John Southern, and show us the grand old engineer spending the evening of his days still busy with scientific pursuits. In spite of the burden of a lifetime of three-quarters of a century, the handwriting is as firm as ever, as is shown by the letter reproduced in facsimile (page 533).

Letter from James Watt to Southern, 20 Dec. 1813.

Dr Sir

I thank you for your criticism
upon the review, which I shall adopt
I am at work upon the proper acct
of my inventions in the Dictionary
which I find it will be a difficult thing
to correct leaving any of the proper
words — I have been employed since
you saw me in collecting materials
for such a history as you mention
but I have my doubts as to my
ability to compile it properly

I remain Dr Sir Yours &c

Decr 20th
1813

J Watt

I return you my best thanks for the Experiments & calculations on the rigidity of tubes you have been so good as to make & which prove satisfactory—

There was no need of any apology for the delay, I was extremely sorry for the occasion of it

Heathfield
Augt. 12
1812

I thank you for returning the dividing engine; for the detention of which no apologies were necessary I am too much guilty of procrastination myself to think it wonderful in others Had I needed the engine I should have reminded you of it, & should you want it again it is very much at your service.

I shall be glad to see you here any evening you find convenient

Heathfield
Nov^{r} 8th
1813

I thank you for your criticisms upon the review, which I shall adopt I am at work upon the Proff^{rs} acc^{t} of my inventions in the Dictionary which I find it will be a difficult thing to correct leaving any of the proff^{rs} words—— I have been employed since you saw me in collecting materials for such a history as you mention but I have my doubts as to my ability to compile it properly

Decr 20th
1813

This last letter refers to the article "Steam Engine," written by Professor Robison for the Encyclopædia Britannica. The professor submitted it to Watt, who was obliged to alter it very greatly and yet without complete satisfaction to himself. It is really quite remarkable how little Watt did actually write for publication. What a pity it is that he never completed the History of the Steam Engine, which he states here that he has in prospect!

The Paper is illustrated by sketches and letters reproduced in facsimile, together with diagrams of other sketches in the letters.

The Institution of Mechanical Engineers.

PROCEEDINGS.

OCTOBER 1915.

The first ORDINARY GENERAL MEETING of the Session was held at The Institution of Civil Engineers, London, on Friday, 15th October 1915, at Eight o'clock p.m.; Dr. W. CAWTHORNE UNWIN, F.R.S., *President*, in the Chair.

The Minutes of the previous Ordinary and Special Meetings were read and confirmed.

The PRESIDENT announced that the Ballot Lists for the election of New Members were opened in May by a Committee appointed by the Council, and the following thirty-eight candidates were found to be duly elected * :—

MEMBERS.

BEDFORD, WILLIAM HOWARD,	Wigan.
HARRISON, HERBERT ARTHUR,	Antofagasta, Chile.
HINDLEY, HAROLD DOUGLAS,	Bourton.
HUSKISSON, WILLIAM MARSHALL,	Manchester.
McGUFFIE, DAVID WILSON,	Glasgow.
POOLE, JOHN,	Manchester.
SAWDEN, HAROLD FISHER,	York.
TAYLER, REGINALD MOSELEY,	Liverpool.

* The Council decided in May that the declaration of this election be postponed until October, thus bringing the new members under the operation of By-law 15.

ASSOCIATE MEMBERS.

Ballinger, Harold, ...	Lincoln.
Bamford, John Theodore, . . .	Birmingham.
Beeching, Harry, ...	Lincoln.
Betterton, Walter, ...	London.
Bishop, Collings Howell, . . .	Birmingham.
Bloor, Frank Robert, ...	Birmingham.
Bray, Herbert Paine, ...	London.
Broadhurst, Francis Arkle, . . .	Bombay.
Brown, Ernest William, . . .	Leighton Buzzard.
Bullwinkle, George Royall, . . .	London.
Edmundson, John Edward, . . .	Manchester.
Fisher, Hubert Frank, ...	Buenos Aires.
Howard, Ernest James, ...	Bedford.
Jack, Thomas, ...	Bolton.
Kennedy, David, ...	London.
MacLachlan, Duncan Robert, . .	Woolwich.
Miller, James, ...	Derby.
Preston, Archibald, ...	Dublin.
Pullman, Hugh, ...	Nottingham.
Rose, William Alexander, . . .	Coventry.
Sells, Martin Perronet, . . .	Wakefield.
Stephens, Charles Vivian, . . .	Cowtheram, India.
Thompson, Robert Francis Stafford, .	Barrow-in-Furness.
Valon, Jean Paul Melville, . . .	Singapore.
Vining, Roy Veitch, ...	London.
Woollen, Harry, ...	Birmingham.
Young, Harry Williamson, . . .	Glasgow.

GRADUATES.

Barstow, Michael William, . . .	Ditchling, Sussex.
Bound, William Henry, ...	Portsmouth.
Dancy, Wilfrid, ...	Brighton.

The President also announced that the Ballot Lists for the election of new members at the present Meeting had been opened by a Committee appointed by the Council, and the following fifty candidates were found to be duly elected :—

MEMBERS.

Clark, William Dores, ...	Angola.
Edgley, Ernest George, ...	Bombay.

Gowing, William Henry, . . .	Kidsgrove.
Payne, Francis William, . . .	London.
Storey, William Edward, . . .	London.
Thornely, George Harry, . . .	Agra.
Whalley, Edmund Bessell, . . .	Rotherham.
Young, John William, ...	London.

ASSOCIATE MEMBERS.

Algar, Stanley Curtis, ...	London.
Banks, Herbert William, . . .	Dartford.
Barr, James Archibald, ...	Paisley.
Belton, Charles Moritz Dunsford, . .	Shrewsbury.
Berry, Henry, ...	London.
Briggs, Roland Hunter, . . .	London.
Burnside, George Barnhill, . . .	Glasgow.
Carratt, Arthur James, ...	Manchester.
Clarke, John Thomas, ...	Tunbridge Wells.
Critchley, Herbert Lawson, . . .	Bulawayo.
Davies, Oswald Bertram, . . .	Hyde.
Ellis, Jack Jefferson, ...	Manchester.
Griffith-Jones, John, ...	Birmingham.
Harrop, Wilfred Marshall, . . .	Wakefield.
Hatch, William Ashton, . . .	St. Helens, Lancs.
Heriot, Charles Adrian Maitland, . .	Buenos Aires.
Huntley, Horace Frederick, . . .	Ulverston.
Ingham, William Jacob, ...	Poona.
Jeffrey, Charles Stewart, . . .	Sydney.
Jervis, Beresford Clayton Lockhart, .	London.
Jones, Percy Lewis, ...	Cardiff.
Jones, Stinton James, ...	Petrograd.
King, Herbert Edward de Courcy, . .	Perth, W.A.
Lambert, Charles Douglas, . . .	Hong Kong.
Lawton, Frederick William, . . .	Birmingham.
Lobley, Henry Denzil, ...	Leiston.
McVittie, Malcolm Johnstone, . .	Darlington.
Minshull, John Williams, . . .	Barrow-in-Furness.
Morris, Reginald Gordon, . . .	Ratnapura, Ceylon.
Peaker, Arthur, ...	Newport, Mon.
Pollard, Edward, ...	Leighton Buzzard.
Price, John, ...	Ystrad, S. Wales.
Royle, John Sanderson, ...	Birmingham.
Saxon, Leonard, ...	Manchester.
Serridge, Herbert, ...	Durban.
Spittle, David George, ...	London.
Steed, Gerald Samways, Captain R.E. .	Gillingham.
Stone, Arnold Alfred Price Dunbar, .	Sierra Leone.

SUTTILL, ALBERT GARBUTT,	Philadelphia.
TRENFIELD, ERNEST JOHN,	Bristol.
WELCH, JOHN FRANCIS WARLOW,	Sheffield.

GRADUATE.

DODDS, THOMAS ERNEST,	London.

The PRESIDENT announced that the following eleven Transferences had been made by the Council:—

Associate Members to Members.

ALLBUT, JONATHAN ENOCH HILL,	Manchester.
BRADY, HUGH WOODHAMS,	Manchester.
BROWN, ALFRED WILLIAM,	Belfast.
CARSON, JAMES,	London.
DEAKIN, GEORGE WELSBY,	Aldershot.
ELLIS, HARRY STEPHENSON,	South Shields.
HUTCHISON, PERCY,	Shanghai.
MACGUCKIN, CHARLES JOHN GRAHAME,	Newcastle-on-Tyne.
POWELL, ERNEST BRECON,	Weymouth.
SELL. ROBERT,	Birmingham.
TURNER, FREDERICK WILLIAM,	Ipswich.

The PRESIDENT said the first thing the members would notice that evening was that they were not meeting in their own building, and the reason for that was known to most of them. There was no alternative in the matter, as under the Defence of the Realm Act the Institution had to give up its building, and the purpose for which it was being used was one of the highest importance. He was told there were now something like two hundred persons employed there, and they were doing good work for the War. The members would have learned from the circular in the last Journal, that although it was a very great inconvenience to the Institution, the Council was glad to have done what was possible for the sake of the country, and so far as possible the Government had met them in a very fair way in the arrangements made for giving up the building.

The Government had also appointed a small but powerful Advisory Committee for the purpose of facilitating and helping researches in the direction of industrial work. The Council had had a conference with that Committee, and had told them frankly how during past years the Institution had promoted research work, and what had been spent on it, and that the Institution was early in the field amongst technical societies in doing work of that kind. That Committee had since suggested that they might perhaps help the Institution by adding funds to those which the Institution applied for the promotion of industrial research. He did not quite know how that would turn out, but at present the Council were dealing with the matter. Discussions had taken place in the Institution with regard to inventions, and it was very satisfactory that the Government had now two really powerful Committees dealing with inventions—one in connexion with the Admiralty, and one in connexion with the Munitions Department. In the case of the latter, they had, in addition to the Committee, an Advisory Council on which were some Members of the Institution, and he believed that very great attention was given to any reasonable inventions which were put forward.

There was a matter on which he desired to obtain informally the advice of the Meeting. The present times were very difficult; the traffic in the streets in the evening was very much obstructed and disorganized; and it had been suggested by Mr. Pendred that the Meetings should be held at an earlier hour in the evening, in order that the members might disperse at an earlier hour and get to their homes with more convenience. Mr. Pendred wrote: "May I ask if the opinion of members could be taken to-night on the desirability of holding the future Meetings during the War at five o'clock instead of eight o'clock? Many members have to get home by train or omnibus, and at the present time all these services are liable to interruption, and are more or less disorganized by the darkness of the streets. Other members are special constables and have duties to perform in the evening; others are engaged in various kinds of war work. For all these reasons I think it would be a real convenience to members if the Meetings were held at an

(The President.)

earlier hour." That was a matter which had to come before the Council, and he was not quite sure, without consulting the Secretary of the Institution of Civil Engineers, exactly at what hour it would be convenient to it for the Meetings to be held. But broadly, he would like the advice of the members on the desirability of meeting at somewhere about five o'clock.

The President asked for a show of hands, and a majority voted for a meeting at five o'clock instead of eight o'clock.

Mr. A. W. Marshall suggested a vote should be taken for six o'clock. He pointed out that five o'clock was a somewhat inconvenient hour, and six or half-past six might meet the views of many. It was not only a question of members themselves, but of the friends invited by members, who were not always able to get away from their business at such an early hour as five, though they might well manage it at six.

The President said that was a good reason, which he would put before the Council. One advantage of five o'clock was that the Meeting could terminate about seven, and the Members would be able to reach home in time for dinner.

Dr. H. S. Hele-Shaw (Member of Council) suggested the Meeting might be held from six to half-past seven, thus confining it to an hour and a half. Many members could not get a meal before they came to the Meeting, and six would meet that difficulty and possibly suit most people.

The President said it must be left to the Council to consider the exact hour, and it was necessary to consult the Institution of Civil Engineers.

A show of hands being asked for six o'clock, there was a rather larger majority in favour of that time.

The following Paper was read and discussed :—

"The Theory of Grinding, with reference to the selection of Speeds in plain and internal work"; by James J. Guest, of Birmingham.

The Meeting terminated at Ten minutes past Nine o'clock. The attendance was 58 Members and 32 Visitors.

Mr. Guest's Paper was read and further discussed at the Engineers' Club, Albert Square, Manchester, on Tuesday, 19th October 1915. Mr. Michael Longridge, *Vice-President*, presided, and 70 Members and Visitors were present.

THE THEORY OF GRINDING, WITH REFERENCE TO THE SELECTION OF SPEEDS IN PLAIN AND INTERNAL WORK.

By JAMES J. GUEST, of Birmingham.

Introduction.—When the Author is asked to advise upon plant installation, the grinding machines proposed are those upon which most discussion arises, and of the points connected with grinding, that of work-speed selection is the least understood. The question which he is most frequently asked is "What is the best work-speed?" The inquirer often volunteers the information that he does not mean revolutions per minute, but the actual surface-speed of the work, which he considers should be some certain fixed amount, at any rate for a given material, such as mild steel. The question is often answered by a direct statement that the speed should be so many feet per minute, but unfortunately for the questioner, each time he asks the question he receives a different reply.

The speeds now recommended vary from 6 to 80 feet per minute; some authorities advise a range from 35 to 70 feet per minute, while others pin their faith to one definite amount—for example, 25 feet per minute. The surface speeds formerly in use were much higher—from 120 to 400 feet per minute—and a belief

in the value of high speeds still exists; so much so indeed that one voluminous writer states it to be a self-evident proposition that the higher the work-speed, the greater the output.

Having received his answer, or looked up the various opinions, the anxious inquirer naturally wishes to know whether the same speed should be used on internal work. Here he finds that there is much more reticence. As improvement takes place in any manufacturing process, it is natural that the speeds advisable should be subjected to change; but in this case the change of practice which has slowly taken place is very great, and is in the unusual direction of lowering speeds.

This universally accepted idea of a standard work surface-speed —independent of the diameters of the work and of the wheel, and of the particular machine used—the author regards as based upon an illusion, probably arising from the similarity of the shape of the work produced by a Universal grinder and a lathe, and a knowledge that there is a (more or less precise) correct work surface-speed in the latter case. The analogy between the actions in a plain grinder and a lathe is false; a better one would be with a circular milling-machine, the cutter-speed in which corresponds to the wheel-speed in grinding.

Some years ago the Author developed the theory of grinding, which he has found of much service, and he presents it here for consideration unbiased by preconceived ideas. The basis of it is given in his Paper before the British Association for the Advancement of Science in 1914, and it is further discussed in his book on "Grinding Machines." It is there treated somewhat discursively, but he will endeavour in this Paper to cut all side issues short, and to present the argument in such a logical form as appeals to engineers.

Limit of Wheel-Speed.—In order to make matters definite and clear, take the case of a piece of work of diameter d, running with surface velocity v, being ground by a wheel of diameter D, with a depth of cut t on the work diameter, and with traverse c per revolution of the work. Also confine the attention initially to

wheels of one fixed grit and grade, and to work of one particular material.

First, consider the effect of time and determine what it is that prevents the speeds, and so the output, from being increased indefinitely. In the case of a lathe or milling-machine, if an attempt be made to increase the speeds continuously, the effect of the heat produced soon enforces a limit, but this does not apply *directly* to grinding, as the abrasive particles (whether corundum, alundum, or carborundum), whose points do the cutting and make the chips, will withstand a very high temperature without injury. The word *directly* is used because the rate of production of heat does produce secondary effects, which formerly frequently controlled the production and even now occasionally do so, although a large flow of water is used. This, however, is a matter aside from the immediate inquiry, and as such is dismissed from the discussion. Similarly, other side issues—for example, the control of the wheel-speed by the material, and ultimately by the abrasive, of the wheel, which arises in the succeeding paragraph—will not be pursued.

In grinding, the speed limit is controlled by the strength of the material of the wheel. The rotation of a wheel causes stresses in its material, proportional to the square of its velocity, and it can easily be shown * that the stress in a wheel depends only upon the speed of its edge V, and not upon its diameter. The decision that a certain factor of safety is necessary limits the highest speed of the wheel-edge to a definite amount. The speed permissible actually varies with the grade of the wheel, but this is foreign to the present issue, and the maximum velocity of the wheel-edge is taken to be V, and to be determined by considerations of safety.

The interaction of wheel and work surfaces may be looked upon from two distinct points of view—the geometrical and the mechanical. If the surfaces go through certain interactions, viewed from the geometrical standpoint, in time t, the effect of taking time $2t$ over the same movements is to lessen the rate of doing the work (and of producing heat) in the same ratio. There may be a minute

* Proceedings, Institution Automobile Engineers, 1911–12, vol. vi, page 331.

difference in the power required, heat produced, etc., due to a small difference in the shape of the stress-strain curve. This variation of the rate of heat production will not, with a good water-supply, disturb matters, and therefore if any lower velocity than V be used, and v lowered in the same ratio, the same action will take place, merely more slowly, and with a corresponding diminution in the rate of output. Hence the wheel is to be used at the highest safe surface-velocity, V, for reasons of production.

Normal Material Velocity alone Effective.—If, instead of having a depth of cut $\frac{1}{2}t$, the wheel only just grazes the work surface,

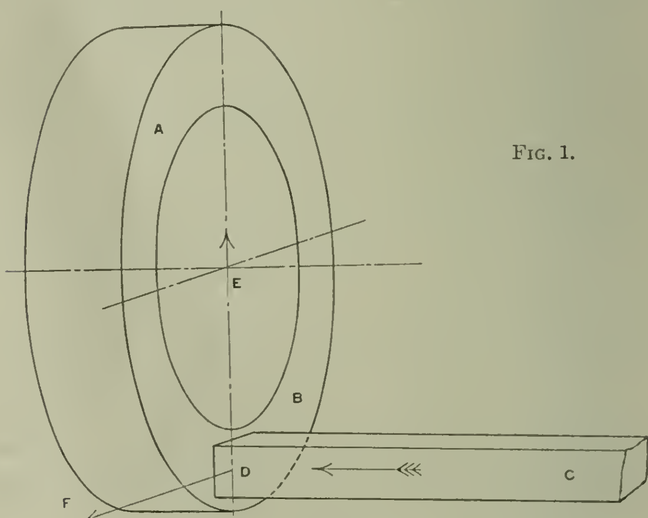


Fig. 1.

neither the rotation nor traverse of the work, singly or combined, will result in any material being ground off. Here the work surface moves by the wheel surface in lines the same as that of the velocity of the wheel particles and perpendicular to this direction (V) respectively. So that, considering a very small portion of the work surface just as it grazes the wheel surface, it becomes clear that no velocity which it has in its own plane can have any effect

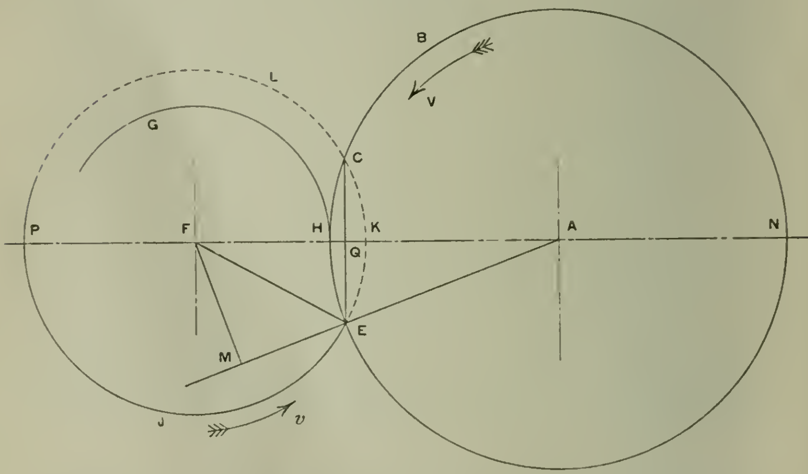
on the actual grinding or on the amount of material removed. Such a velocity merely presents quantity of work surface to the wheel.

In grinding, therefore, the third component of the work at the wheel-face must be the effective one, and, geometrically considered, it must be the fundamental controlling factor. The Author calls this quantity the normal material velocity, as it is the component of the work velocity which is normal to the wheel surface. To illustrate this, suppose that a cup-wheel with a flat face AB, Fig. 1, be rotating, and a bar of steel CD be held with its end against the wheel-face, so that the length CD is perpendicular to the face AB. If the bar is pushed lengthwise directly into the wheel, it will receive this normal material velocity only, and will be ground away. If it be moved sideways only, whether parallel to DE or DF, no material will be ground away. If the bar received the three movements simultaneously, the amount ground away would depend on the normal velocity only. If the bar were pushed rapidly into the wheel-face, it would disintegrate it and cause the wheel to waste away. If it be fed in very slowly indeed, the particles of the wheel will gradually become dull and then polished; the wheel-face will then be "glazed" and it will be difficult to force the bar in. These two effects limit the possible amounts of the normal material velocity; between them lies the region of grinding within which there is some value of this velocity (depending chiefly upon labour and wheel costs), which may be regarded as the best.

Value of the Normal Material Velocity.—In the case of circular grinding, which is under consideration, where an amount t is being removed from the diameter, the work must have some normal material velocity into the wheel at the arc of contact, although this arc is so short. It is now necessary to find the value of the normal material velocity in this case of plain (or external) grinding. In Fig. 2 (page 548) the contact of the wheel and work is shown on a distorted scale for the sake of clearness—the depth of cut having been made very excessive. Here A is the centre of the wheel BCE, and F the axis of the work GHEJ; while KCL represents the continuation of the work surface JE as it would have been if not ground away,

so that HK is the depth of cut or $\frac{1}{2}t$. The wheel is rotating in the direction marked by the arrow V and the work in the same direction, marked by the arrow v. The part of the work GHEKCL is ground away, so that the arc of contact is HE. If the number of cutting points on the wheel-face be estimated and the size of the chip deduced, it will be found that the arc of contact extends a little above H towards C, but that this distance is so small compared with HE that it need not be considered. Join AE and draw FM perpendicular to it (produced). Produce AKHF to cut the

FIG. 2.



wheel and work circles in N and P respectively, and join CE cutting this line in Q, and join FE. Now (by Euclid iii. 35) the product of chords in a circle are equal, and

$$\therefore \text{HQ} \times \text{QN} = \text{QE}^2$$

$$\therefore \text{HQ} = \frac{\text{QE}^2}{\text{QN}},$$

similarly

$$\text{KQ} = \frac{\text{QE}^2}{\text{QP}}$$

and

$$\therefore \text{HK} = \text{HQ}+\text{KQ} = \text{QE}^2\left(\frac{1}{\text{QN}} + \frac{1}{\text{QP}}\right).$$

Now HK is the depth of the cut or $\frac{1}{2}t$, and in practice is of the order of 0·001 inch, so that, similarly to its parts QH and QK, it is small compared with the diameters of the wheel and of the work. Hence QN may be taken as equal to HN or D, and QP as equal to KP or d in the above equation. Also, since the base HQ of the curved triangle HEQ is so small, QE may be considered as equal to HE or s.

Substituting these values in the above equation, it becomes

$$\tfrac{1}{2}t = s^2\left(\frac{1}{\mathrm{D}} + \frac{1}{d}\right),$$

so that the length of the arc of contact is

$$s = \sqrt{\frac{\mathrm{D}dt}{2(d+\mathrm{D})}} \quad . \quad . \quad . \quad . \quad (1)$$

Now at E the particles of the work are moving with velocity v perpendicular to FE, and this velocity will have components v_1 (the normal velocity of the material) along EA and v_2 along the wheel-face EH, perpendicular to EA. These directions are perpendicular respectively to the sides FE, FM and ME of the triangle FME, so that it is a triangle of velocities, and

$$\therefore \quad v_1 = \frac{\mathrm{FM}}{\mathrm{FE}}\,v.$$

Now $\quad \mathrm{FM} \times \mathrm{AE} = 2 \times \text{Area of triangle FEA}$

$$= \mathrm{EQ} \times \mathrm{FA}$$

or $\quad \mathrm{FM} = \dfrac{\mathrm{EQ}\times\mathrm{FA}}{\mathrm{AE}}.$

But $\mathrm{FA} = \mathrm{AH}+\mathrm{FK}-\mathrm{HK} = \frac{1}{2}(\mathrm{D}+d-t)$, but as t is so small compared with $\mathrm{D}+d$, it may be omitted, and the equation becomes

$$\mathrm{FM} = s\,\frac{d+\mathrm{D}}{\mathrm{D}}$$

and $\quad \therefore \quad v_1 = \dfrac{\mathrm{FM}}{\mathrm{FE}} \times v = s\,\dfrac{d+\mathrm{D}}{\mathrm{D}} \times \dfrac{v}{\frac{1}{2}d} = 2sv\,\dfrac{d+\mathrm{D}}{d\mathrm{D}} \quad . \quad . \quad (2)$

$$= v\sqrt{2t\frac{d+\mathrm{D}}{d\mathrm{D}}} \quad . \quad . \quad . \quad (3)$$

This, then, is the value of the normal material velocity at the point E, and will control the grinding at that point.

It cannot, however, be concluded immediately that it controls the grinding completely, as the normal velocity varies all along the arc from the value zero at H to the amount just found at E. Equation (2) states that $v_1 = 2vs \frac{d+D}{dD}$,

and, as in the proof of this, no specification as to the value of the depth of the cut has been made, this applies all along the arc HE—that is, any other point in HE may be supposed to correspond to the point E for a smaller depth of cut and very slightly less diameter of work. Since the quantities v, d and D are the same within insignificantly small amounts, this shows that the value of v_1 at every point along the arc of contact is proportional to the length of the arc s measured from H to that point. Hence, whether the arc of contact in any case is long or short, provided that the final value of v_1 is the same, a cutting particle is subjected to the same normal material velocity at corresponding intermediate points; so that whether a cutting point, in its history of getting blunt, passes a large number of times over a short arc or a fewer number of times over a longer arc, it receives equal amounts of action under equal normal material velocities. Just the same applies to particles whose points lie a little lower in the wheel than those which at any moment are taking their full cut, so that the total result is that the history of all particles is similar, provided that the final normal velocity of the material at E is the same. Hence the quantity $v\sqrt{\frac{2t(d+D)}{dD}}$ is the controlling factor, and if it is too large the wheel will wear away unduly, while if it be too small the wheel will glaze. In the first part of the history of a cutting point the normal material velocity is very small and the action is a glazing one; in the latter part it is greater and the action finally fractures the particle or forces it from its bond in the wheel.

The force of the cut on any particle will depend on the normal material velocity, and it is the force which fractures or dislodges

the particle of abrasive; beyond this the actual value of the force is not of present importance. The action gradually blunts the particle and so increases the width of the chip; this increases the force produced by the same normal velocity, so that a particle is not immediately fractured or dislodged by a certain normal velocity, but such an event occurs after a certain amount of action.

Let $\sqrt{2a_1}$ be the value of v_1 at which glazing just takes place, and $\sqrt{2a_2}$ that at which the wheel wears unduly. Some intermediate value $\sqrt{2a}$ will be the best value, and for it the equation becomes

$$\frac{d+D}{dD} \times tv^2 = a \quad . \quad . \quad . \quad . \quad (4)$$

This is the equation giving the best value of the work-surface velocity v, and it shows that it does not depend on the nature of the wheel and of the material ground only, but also upon the diameters of both work and wheel, and upon the depth of cut.

If v be increased from this best value, the normal material velocity gradually rises until the value $\sqrt{2a_2}$ is reached, at which the wheel wastes away too rapidly; its value is not a precise one, but is a matter of the balance of wheel and labour costs. When the quantities are so large that the grinding is done in two operations, a higher value of v_1 should be used in the rough grinding than would be satisfactory in cases when parts are finished at once. The best value of a is therefore also somewhat higher in the former case.

Equation (4) shows that some function of d, D, v and t is to be constant in order that the wheel should work well; but even in grinding one particular piece of work with one definite wheel (so that d and D are given), the two quantities v and t may be varied, and yet the equation be satisfied perfectly.

The Material Removed.—The rate of removing material is $\frac{1}{2}vt$ per unit width of effective wheel-face, and this is limited by the power supplied to the machine. By the expression "effective wheel-face" is intended the amount which takes the cut; if the traverse c lies between the half and the full width of the wheel-

face, then the wheel-face tends to keep flat, and is effective over a width c, and the rate of removing material is $\frac{1}{2}vtc$.

The work done in removing metal by a single point cutting-tool in a lathe is approximately proportional to the volume of the material removed. Experiments upon cutting-forces show that this work increases as the section of the chip diminishes: a result to be expected, but the increase is at a slow rate. The chips taken in grinding are of very small cross-section—of the order of a thousandth of an inch both in breadth and thickness—and no experiments have been made upon chips of such a size, or taken with cutting points, whose facets are disposed so irregularly as those of an abrasive particle. The results above referred to may, however, be considered as applying to the case, leading to the conclusion that the work done in removing metal by a definite wheel is practically the same over usual variations of the depth of the cut, although it will actually be a little less with the heavier cuts. Also it leads to the conclusion that wheels of the larger grits will remove material at a slightly less cost in energy than wheels of the finer grits.

While no experiments have been made on the work of cutting metal, at the rate at which grinding chips are taken, the stress-strain curve can only alter very slightly if the rate of taking them be altered to the extent of the variation which the tangential component of the work velocity produces on the relative tangential velocity of wheel and work; it can only alter little, even over the variation of wheel-speed (4,000 to 7,000 feet per minute) used in practice. Hence the work of removing metal can only alter by very little with speed variations of wheel or work. Therefore the work done in grinding off metal is proportional to the volume removed—that is, the rate of grinding, $\frac{1}{2}vtc$, depends on the power used.

Hence for the work and wheel under consideration, the quantity vtc depends upon the power which is supplied to the machine, and cannot exceed a certain amount b, while for production reasons it is to be kept up to that amount. In use, a machine should not be run so hard that the power taken is close on the possible limit; this

would lead to trouble sooner or later (for example, the machine might slow from belt slip), and b is to be taken as the highest safe working quantity.

The Controlling Expressions.—There are therefore two conditions, $v^2t = a\dfrac{dD}{d+D} = c$ and $vt = \dfrac{b}{c}$, which serve to determine the values of v and t for any particular case, and they are sufficient for the purpose.

Checking Wheel Waste and Glazing.—They will indicate the procedure to be adopted in the various cases. Suppose that the wheel in use is wearing too rapidly. The first impulse is to reduce the cross-feed so as to lessen the intensity of the action, and check the wear by this means. The years of practical experience, however, have proved that it is better to reduce the work-speed, and that the wheel will then last properly, and this is generally recognized as the best modern practice. Another method advised is to reduce the wheel-speed, but this the Author cannot recommend. Inspection of the above equation indicates a somewhat different course to be the most advantageous.

As the wheel is wasting, v^2t is too high and must be lowered. If t be reduced, this is effected, but it is clearly more effective to reduce v. For example, if it were necessary to reduce v^2t to $\frac{1}{4}$ its value to stop the waste, and t alone were altered, it would be reduced to $\frac{1}{4}$ its value; while the same result would be effected by reducing v to half its original amount. In each case the output is sacrificed as vtc is lowered—to $\frac{1}{4}$ of its original value in the first case and to $\frac{1}{2}$ in the second, which is therefore the better. This sacrifice of output is, however, unnecessary. The problem is to alter v and t so that v^2t is reduced to $\frac{1}{4}$ of its previous value, while vt is unaltered. Solving the simultaneous equations, the result shows that v must be lowered to $\frac{1}{4}$ of its original value, and t simultaneously increased to four times its initial value. This stops the wheel waste, and at the same time keeps up the output.

Generally, then, the equations lead to the rule that if the trouble

is wheel-waste, the work-speed is to be decreased far more than is sufficient to check it, and the cross-feed is to be proportionally increased; if the wheel still wears too fast, proceed further in the same manner.

Conversely, if the wheel glazes, the work-speed must be increased and the cross-feed simultaneously decreased so as to keep within the power limit.

Securing Maximum Output.—Suppose now that the wheel is behaving well, showing that v^2t is correct, but that the machine can take more power, and hence give more output, then v^2t is to be kept constant, but vt increased. This can be done by decreasing v in any ratio k and increasing t in the ratio k^2. For example, suppose that v be lowered to $\frac{3}{4}$ of its initial value, then t should be increased in the ratio $(\frac{4}{3})^2$ (or by 78 per cent.), with the result that v^2t would be unaltered, but vt, the amount ground off, would be increased in the ratio $\frac{4}{3}$ (or by 33 per cent.). And this is a general law, so that the slower the work-speed and the deeper the cut, the quicker will the stock be removed. Modern practice tends towards slow speeds, partly for the reasons shown above.

The question now arises as to where the work-speed reduction should stop, for the ultimate result is that, in order to remove the material at the highest rate, the whole grinding allowance should be removed by a deep cut at a single traverse. This is immediately opposed to one of the principles of grinding which give it the primary quality of accuracy—namely, that the stock is to be removed in small amounts, so that any gradual distortion of the work is minimized and the wheel-wear also rendered of no effect. The greatest permissible reduction of work-speed is therefore ultimately governed by the liability of the work to distort, but in practice no machine is supplied with nearly enough power for such a state of affairs to arise, and the limit is encountered much earlier by reaching the maximum value (vtc) of the power supplied to the machine.

In finishing, the cross-feed must be exceedingly small (no mechanical feed finally), but practice differs considerably as to

finishing speeds, advice that the ordinary speed should be increased and that it should be diminished being given equally. As the cut in finish grinding is exceedingly small, the normal material velocity will be small and the wheel will tend to glazing. This is desirable, as the wheel must not wear much in finishing; but nevertheless, as t is so much reduced (to $\frac{1}{4}$ or so of its previous amount), v may be safely increased (by 25 per cent. or more) and yet v^2t will be much reduced. Finish ultimately depends upon the number of cutting points which have passed over the work-surface, and from this point of view wheel-speed and the truing alone count; from the principle above mentioned as to the securing of accuracy, an increase of work-speed is desirable, and also the required finish may be obtained earlier. The only factor militating against the increase of work-speed for finishing is the greater tendency to vibration, but this is small.

Effect of Work-Diameter.—Now that the manner of dealing with work of a definite diameter, ground by a wheel of a given diameter, has been considered, the effect of change of work-diameter and of wheel-diameter may be discussed. The equations $v^2t\,\frac{d+\mathrm{D}}{d\mathrm{D}} = a$ and $vt = \frac{b}{c}$ must hold simultaneously, the first dependent on the wheel substance and the material ground, and the second on the machine. Dividing one equation by the other, the equation

$$v = \frac{ac}{b} \times \frac{d\mathrm{D}}{d+\mathrm{D}} \quad . \quad . \quad . \quad . \quad (5)$$

is obtained. It shows that the effects of wheel- and work-diameter are interrelated, and hence, in order to obtain some idea of the effects of variation, it is best to consider numerical cases.

Suppose that the work be 4 inches and the wheel 14 inches in diameter, and that for the machine in use it were found that a work surface-speed of 30 feet per minute and a diametrical reduction of 0·00125 inch gave the best results. If the wheel wore down to 10 inches diameter (being kept up to the initial surface-speed, usually 5,000 feet per minute) the question would arise as to whether any change should be made in the work

surface-speed and in the feed. From equation (5), but substituting the original values of v, d and D, we have $\frac{ac}{b} = \frac{30(4+14)}{4\times 14}$, and hence for the work-velocity with a 10-inch wheel we have

$$v = \frac{30(4+14)}{4\times 14} \times \frac{4\times 10}{4+10} = 27\tfrac{1}{2}$$

so that the best work-velocity is little affected, there being only 8 per cent. difference, and generally the effect of the wear of the wheel on the best work-speed in external grinding is small. It may be noted that, if the same work-speed be preserved, the normal material velocity is higher and the wheel appears somewhat softer as it wears, and still more so if its surface-speed is not kept up to the value V.

The work-diameter, however, varies more widely than the wheel-diameter and produces correspondingly large effects. Suppose that work of 1 inch diameter is to be ground, the work-speed would then be

$$v = \frac{30\times 18}{4\times 14} \times \frac{1\times 14}{1+14} = 9 \text{ feet per minute.}$$

Since vt is constant, $t = 0\cdot 004$ inch. After calculating the values for work of 16 inches diameter also, the results may be tabulated thus :—

Work-diameter	inches	1	4	16
Work-speed	ft. per min.	9	30	72
Cross-feed	mils on diam.	4	$1\frac{1}{4}$	$\frac{1}{2}$
Revolutions per minute		35	$28\frac{1}{2}$	17

The surface-speed of the work therefore varies considerably—much more so, in fact, than the rate of revolution does. Such large variation of work-diameter would hardly occur in practice, as the 1-inch and 16-inch work would be done on different machines, but it illustrates the point in question markedly. In practice the following difficulties usually modify these natural speeds.

Work of Large and Small Diameters.—The force of the cut of the wheel on the work is the same in all these cases, and although the effect may be checked by steadies, this force will probably cause

slender work to vibrate. In this case the force must be reduced, which sacrifices output and lowers vt. In order, then, to keep $v^2t\frac{d+D}{dD}$ constant, and the wheel under good working conditions, v must be increased and t lowered. The extent to which it is necessary to do this will depend on the flexibility of the work—it may only be little. From this result it is seen that work of small diameter should run at a lower surface-speed than larger work in the same machine, but that the tendency to chatter modifies the speed which can actually be used.

The large diameter work presents another point of interest. Here it will be noticed that the work-speed is so much higher that the cross-feed is reduced nearly to the amount of a finishing cut, and is such as can only well be used when the work is very true, and is therefore unsuitable for preliminary and general grinding.

Now if v be lowered and t increased in such proportions as to keep the normal material velocity unaltered, vt—that is, the power per unit width of wheel-face—is increased. The machine is supposed to be already in use up to the reliable limit of its power, and this leaves only one resource (apart from changing the wheel for one of a slightly softer grade), namely, to reduce the effective width of the wheel so as to concentrate the same power over a lesser axial space. This increases $\frac{vt}{c}$, and so permits a heavier and satisfactory cross-feed to be used with a lower surface velocity.

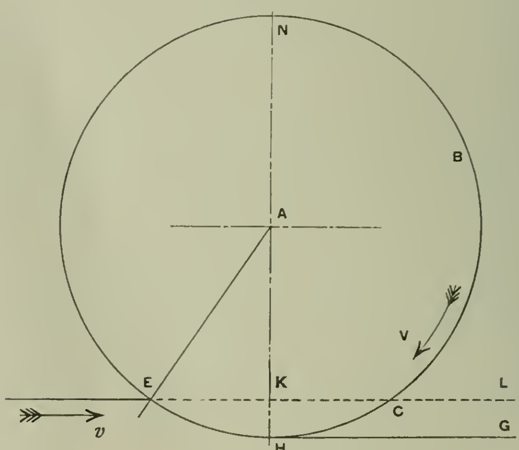
Narrowing the Wheel-Face.—The width of the wheel in full use may be reduced by lessening the traverse c, but as the number of traverse speeds is limited, and as the traverse should be between $\frac{5}{8}$ and $\frac{7}{8}$ of the wheel-face, this method is seldom really available unless the advantage of such a traverse be sacrificed and a lesser one (which tends to make the wheel-face wear convex) used. For a few articles this is best, but, for any quantity, the wheel should be changed for a correspondingly narrower one, and at the same time the traverse correspondingly reduced.

In addition to the want of original truth of work, rendering fine cross-feeds undesirable, they are difficult to maintain if the

absolute distance between the work and wheel axes can vary (by spring of parts, etc.), as is especially the case in internal grinding. Furthermore, they afford little flexibility, and small variations and errors affect fine feeds proportionally more than they affect heavier feeds.

Surface Grinding.—If in the expressions 1, 4 and 5 the work-diameter be supposed to be increased until it becomes exceedingly (infinitely) great, the work becomes flat, and the case is that of

Fig. 3.



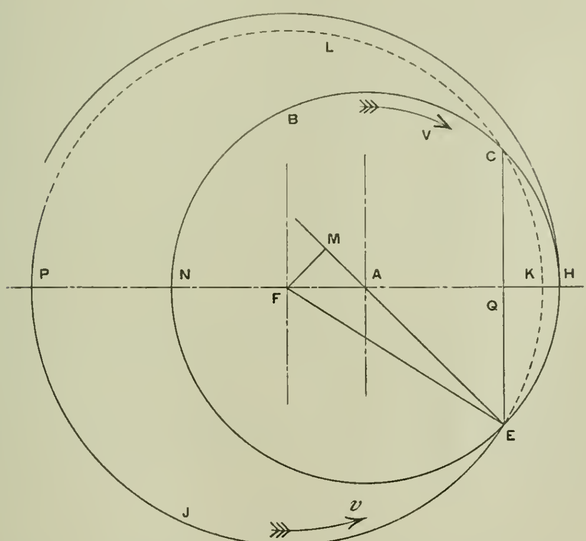
surface grinding with a disk wheel; and if it is supposed to vary further, changing its sign and diminishing, the case becomes that of internal grinding. The expressions of the various quantities then become :—

	For Surface Grinding.	For Internal Grinding.
s	$\sqrt{\frac{1}{2}Dt}$	$\sqrt{\dfrac{dDt}{2(d-D)}}$
a	$\dfrac{tv^2}{D}$	$\dfrac{d-D}{dD}tv^2$
v	$\dfrac{ac}{b}D$	$-\dfrac{ac}{b}\dfrac{dD}{d-D}.$

The negative sign in the last expression indicates that the direction of work rotation is to be reversed in internal grinding. In the other expressions for the internal case, the sign of t is changed also. These values may be deduced from Figs. 3 and 4, using the same reasoning as previously.

Internal Grinding.—Passing by the case of surface grinding, the more interesting case of internal grinding is reached. Here both d

FIG. 4.



and D vary considerably, but any change in either will usually produce a more than proportional change in $d - \mathrm{D}$, and hence it is an important factor. Its change as the wheel wears down in grinding a number of similar holes causes the chief difficulty in internal work.

Neglecting the sign of v, its value is $\frac{ac}{b} \times \frac{d\mathrm{D}}{d - \mathrm{D}}$, which can be calculated for any particular values of the work and wheel diameters by using the value of $\frac{ac}{b}$ derived from the previous example,

provided that the internal grinder uses the same power per inch of wheel-face as the plain grinder does, and that a wheel of the same grit and grade be employed. Taking the case of a 4-inch hole (in the previous example the work was 4-inch diameter, but external), suppose that a wheel 3 inches in diameter be used to grind it. Substituting these values $v = \frac{30 \times (4+14)}{4 \times 14} \times \frac{4 \times 3}{4-3} = 116$ feet per minute, and the corresponding value of t is $0 \cdot 00125$ inch $\times \frac{30}{116}$, or $\frac{1}{3}$ of a thousandth of an inch; if, however, a wheel $3\frac{1}{2}$ inches in diameter were used, the values would be $v = 270$ feet per minute, and $t = 0 \cdot 00014$ inch. Thus when the size of the wheel approaches that of the hole, the difficulty of a very fine cross-feed again arises, for the springiness of an internal grinding spindle renders such a cross-feed unusable. As in the case of external work, the difficulty is to be met by increasing the power used per unit width of wheel-face—that is, by decreasing the width of wheel used. Reduction of the wheel-face, it is to be noted, does not directly imply loss of output, which mainly depends on the power utilized or on the total force of the cut.

Internal grinders are usually supplied with less power than plain grinders, for work of equal diameter, and this makes the wheel which can be used still narrower. The great disadvantage of a narrow wheel is that there is less grinding substance in it, so that the difficulties caused by the diminution of its size occur more rapidly.

Effect of Wheel-Wear and Size of Wheel.—The correct understanding of these difficulties is important as regards internal grinding, and they are shown most clearly graphically. In Fig. 5 (which is taken from the Author's book on Grinding, page 264) is shown the effect of change of size of the wheel in grinding work of 4-inch diameter, the quantities being based upon those of the example taken, in which the power used would be about 2 h.p. per inch of wheel-face. Along OA is set off the wheel diameter, and along OB the work-surface velocity for the case of external grinding, the dotted curve OCD being obtained from the equation (5)

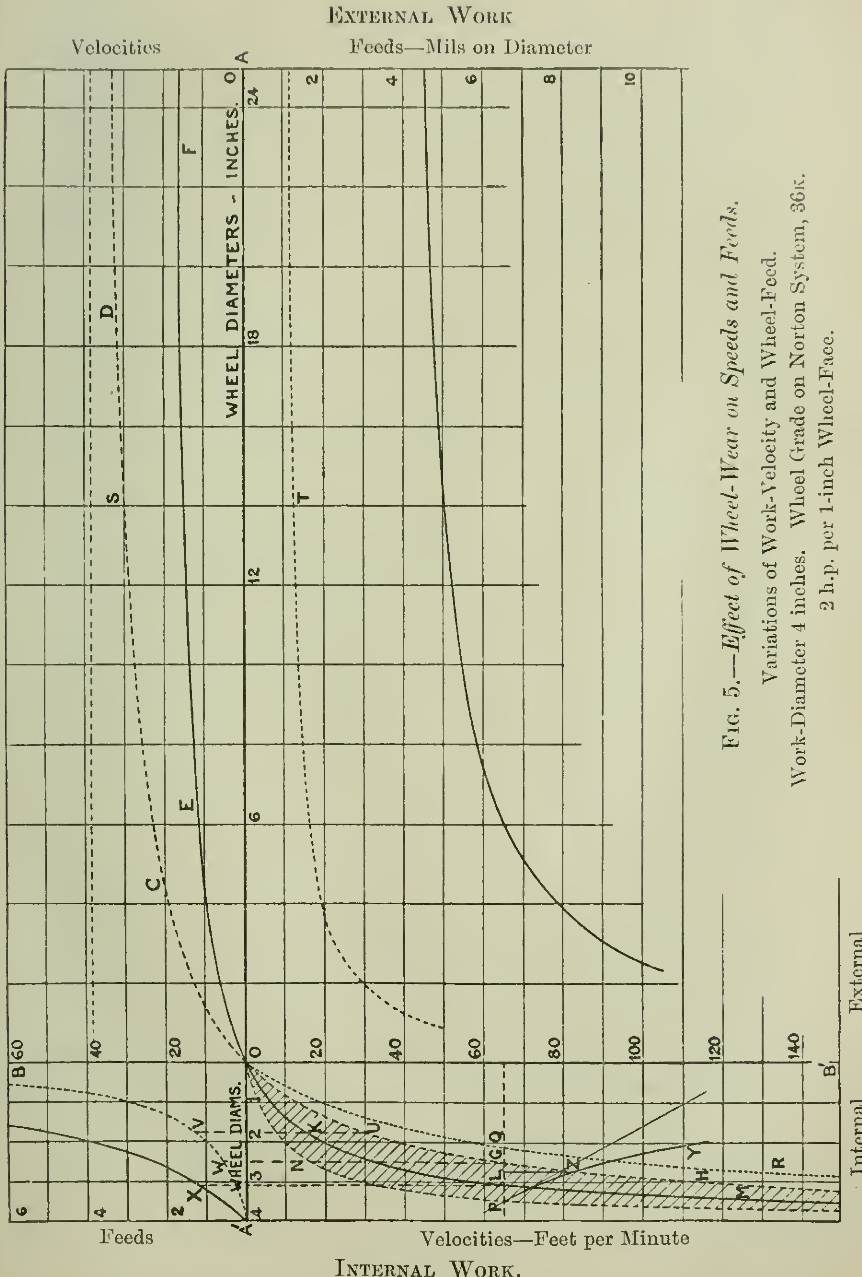


Fig. 5.—*Effect of Wheel-Wear on Speeds and Feeds.*

Variations of Work-Velocity and Wheel-Feed.

Work-Diameter 4 inches. Wheel Grade on Norton System, 36K.

2 h.p. per 1-inch Wheel-Face.

where $v = \frac{ac}{b} \times \frac{dD}{d + D}$. The corresponding feeds t are set off downwards from the line OA, the scale being given on the right of the diagram, and the dotted curve T so obtained.

The original 14-inch wheel required a work-velocity of 30 feet per minute, which would fall to $27\frac{1}{2}$ feet per minute for a 10-inch wheel, and to 23 feet per minute for a 6-inch wheel. If a 24-inch wheel were used, the work-velocity would be 33 feet per minute, but however the wheel diameter were increased, the best work-speed would never exceed $38\frac{1}{2}$ feet per minute indicated by the broken horizontal line, to which the curve OCD, a rectangular hyperbola, is asymptotic. If the same power were concentrated upon a wheel of half the width, the speed curve would be the full line curve OEF, and corresponding feeds would be given by the full line curve below.

The right-hand side of the diagram gives the case for external grinding, and shows that variation of wheel diameter produces little difference on the speeds and feeds suitable for work of a given diameter, and practically this small difference is covered by the range of the normal material velocity within which the wheel works well. The curves for internal grinding are shown on the left, OA′ and OB′ being the axes of wheel diameter and work-speed respectively. The curve OGH is actually a continuation of the curve DCO, but its inclination is very different, and it is asymptotic to the bounding vertical line, whereas on the external side it was asymptotic to a horizontal line.

The work-speeds and feeds for $3\frac{1}{2}$-inch and 3-inch wheels have already been given, and it was observed that the feeds, which also may be taken from the dotted curve A′WV in the quadrant BOA′, turned out to be unworkably small. To remedy this, suppose that a wheel of half the face width be taken, so that 4 h.p. is now used per inch of wheel-face; all the velocities are now halved and feeds quadrupled, the former being given by the full-line curve OKL and the latter by the curve A′X. A 3-inch wheel would now require a work-surface speed of 58 feet per minute and a feed of $\frac{4}{5}$ of a thousandth of an inch on the work-diameter in order to work at its

best, and these would be usable. Now this full curve OKLM gives the best normal material velocity when 4 h.p. is used per inch of wheel-face, but actually there is a range, that between $\sqrt{2a_1}$ and $\sqrt{2a_2}$, which may be used satisfactorily. Suppose that halving its value would just not make the wheel glaze, and that doubling it would make it waste excessively (these are wide limits, and taken for the sake of clearness), the curve ONP then gives us the limit on the glazing side, and the curve OGH the limit on the wasting side, and the space between them represents conditions under which grinding can successfully take place.

All these curves, being derived from different values of a—that is, of the normal material velocity—are of the same type, passing through O, and being asymptotic to the bordering line. A curve OQR, shown in dots, would indicate a stage of very excessive wheel-wear. Now suppose that a surface speed of 65 feet per minute be given to the work; this is indicated by the horizontal line PLGQ, and the corresponding feed, indicated by the point X, is rather more than a thousandth of an inch. The point P, which gives a $3\frac{1}{2}$-inch wheel, is on the glazing line which indicates that a $3\frac{1}{2}$-inch wheel would just glaze and any larger one would glaze badly. In grinding a series of holes the wheel would slowly wear down, and as it did so it would work better until—when the diameter was reduced to 3 inches—the point L on the full-line curve was reached, when it would be working at its best. Further wear of the wheel would tend to make it waste, until, when it had worn down to $2\frac{1}{2}$ inches, it would reach the point G on the bordering curve, and be then wearing excessively.

The wheel can be used still further with the work at 65 feet per minute, towards the point Q, but the cross-feed must then be reduced to prevent the waste, and output will be sacrificed. The width PG thus gives the range through which a wheel may wear in internal grinding without causing trouble. Owing to its shortness the grinding regime alters rapidly, there being little range between glazing and wasting away. What is to be aimed at is to start with the wheel condition on the glazing curve, chamfering the edge if need be; as the wheel wears, it first works better and

afterwards worse, and on reaching the stage of undue wasting the work-speed has to be lowered. If it be lowered considerably (e.g., from 65 feet per minute at G to 15 feet per minute at N), it may be restored to the glazing condition again.

For the sake of lucidity, one factor has not yet been included, namely, the decrease in surface-velocity of the wheel, as its diameter decreases, for in the diagram the wheel surface-velocity is supposed to be kept constant, which would involve increasing the speed of the internal spindle frequently as the wheel wore down—a case seldom provided for in internal grinding machines. The effect of keeping the wheel spindle-speed (instead of the wheel surface-speed) constant is to decrease the length of PG or the amount of wheel wear before wasting. Taking a geometrical view, it is clear that the normal velocity must be proportional to the wheel surface-speed, and must therefore drop as the wheel wears down at constant revolutions per minute—that is, the limiting normal material velocity instead of being $\sqrt{2a_2}$ must be $\sqrt{2a_2 \times \frac{D}{D_0}}$, where D_0 is the original wheel-diameter at P. Thus the boundary curve instead of being $v = \frac{a_2 c}{b} \times \frac{dD}{d-D}$ (or OGH) will be $v = a_2 \frac{D^2}{D_0^2} \times \frac{c}{b} \times \frac{dD}{d-D}$, and by giving to v its initial value v_0—the value at P—this becomes an equation for D, and is easily solved algebraically. On the diagram, however, it is best solved by noticing that the elimination of v between $vD^2 = v_0 D_0^2$ and $v = \frac{a_2 c}{b} \times \frac{D}{d-D}$ gives the same equation for D. This, expressed geometrically, means that, by drawing the quasi-hyperbola $vD^2 =$ constant—which has OA′ and OB′ as asymptotes—through P to cut the curve OGH, the point of intersection Z gives the wheel-diameter desired. Drawing the hyperbola or—what gives nearly the same result—its tangent at P, we obtain $2\frac{3}{4}$ inches as the limiting wheel-diameter instead of $2\frac{1}{2}$ inches.

Generally, if the surface-speed V of a wheel changes, the equation $v^2 t = a \frac{dD}{d-D}$ becomes $\frac{v^2}{V^2} t = k \frac{dD}{d-D}$, since the normal

material velocity must be proportional to the wheel-surface velocity. If wheel spindle speed remains constant at n revolutions per minute, this gives $v^2t = k\pi^2n^2 \times \frac{dD^3}{d-D}$. If the power taken still remains the same, vt has its former value, $\frac{b}{c}$, which furnishes the second equation necessary for the determination of results. The elimination of t for n revolutions per minute then gives $v = \frac{k\pi^2nc}{b} \times \frac{dD^3}{d-D}$, the same equation as has been found more directly for dealing with the special case of wheel-wear in internal grinding.

More closely calculated values of the wheel-diameters in the above example are, 3·48 inches at P, 2·51 inches at G, and 2·86 inches at Z, so that G shows a 28 per cent. reduction of wheel-diameter and Z an 18 per cent. reduction.

Thus the difficulty of internal grinding chiefly consists in meeting the continuous change of regime due to the direct effect of the decreasing diameter of the wheel and to the secondary effect due to loss of wheel surface-velocity, and so far from the work velocity being kept constant, it is to be changed as often as necessary to meet the altered state of the grinding.

The Arc of Contact.—No reference has so far been made as to the effect of the length of the arc of contact in internal grinding; it is commonly regarded in practice as the cause of the trouble of the wheel behaviour. The Author has previously shown, however, that, owing to the proportional distribution of normal material velocity in the arc of contact, the actual length of an arc has no direct influence in grinding, provided that there is room between the abrasive particles of the wheel for the chips produced. Equation (1) gives

$$s = \sqrt{\frac{Ddt}{2(d \pm D)}},$$

and

$$\therefore \quad s = \sqrt{\frac{t^2v^2}{2a}} = tv\sqrt{\frac{1}{2a}};$$

so that the length of the arc of contact is proportional to the power per unit width of wheel, or the area of effective contact (i.e., the

length of the arc by the traverse) measures the power used at the grinding point and the output.

Effect of Grade.—Lastly, consider the effect of using a wheel of a different grade. The greater the amount of bond employed, the greater the force upon the cutting points which is necessary to dislodge the particles of abrasive and the "harder" the wheel is. It therefore will withstand, and requires, a greater normal material velocity to work well, and hence the work-surface velocity employed must be higher. The value of vt for a given power-supply is less, because the particles get more blunt before they are dislodged.

Conversely with softer wheels, the speeds must be lower, and the output for a given power-supply is greater, which leads to their employment in order to secure the output, and hence to a further lowering of speed in modern practice.

Conclusion.—In the presentation of the Author's theory of speeds and feeds and the deduction of the methods for meeting the various difficulties, he has made use of as few properties of the wheel and work as possible, in order that the results shall be of very general application. In those cases where he has taken numerical examples in order to display the reasoning more clearly, the methods employed have been generally applicable, and the results may be considered to be typically representative.

The Paper is illustrated by 5 Figs. in the letterpress.

Discussion in London.

The PRESIDENT, in moving a vote of thanks to the Author, said he did not profess to be an expert in the matter of grinding, and was quite prepared to say that there was a good deal in the Paper which was beyond his range of experience; but he had no hesitation in stating that, as far as he could judge, the Paper was one which really made a step in advance in one particular department of mechanical work, and he had no doubt it was really a very valuable Paper. It was not very easy to discuss, but he hoped there were engineers present who had had experience of grinding work, a work which was comparatively modern in its application, and extremely interesting. It had made immense way within a comparatively short time.

The motion was carried with acclamation.

Dr. H. S. HELE-SHAW (Member of Council) said personally he was in no sense an authority on grinding, though he had been a user of several grinding machines. The interesting point in regard to the Paper appeared to him to be that it was the birth of a theory on a most important subject. He had come that evening hoping to get one or two points elucidated. One point he could not altogether understand was the question of the importance of changing the work-speed by a comparatively small amount. If the work-speed were, say, 30 feet a minute, and it was changed to 60 feet a minute, it was changed 100 per cent.; but supposing the grinding wheel was run at 6,000 feet, which was not an uncommon velocity, and it was changed to 6,500, the actual relative change of speed of the two surfaces was enormously greater than the change of 100 per cent. in the case of the work. There might be others who had had a difficulty in understanding why a change in the work-speed, which might mean only a small change in relative speed, made such an apparent difference; the velocity of the emery wheel could be changed to a very much greater positive extent, and therefore the

(Dr. H. S. Hele-Shaw.)

relative velocities of the two surfaces were working in contact without apparently making nearly as much difference. The Author would be rendering a service if he would elucidate that point, which did not appear clear to most people who actually used grinding machines. He had written on the subject to a man who was certainly a high authority—the works manager of The Churchill Machine Tool Co., of Pendleton—and he had given an example of the great range that was possible in practice. That gentleman said: "I was recently consulted by a customer about the installation of a grinding machine for grinding a combined steel piston and piston-rod, the diameter of the piston being about $4\frac{1}{2}$ inches and the rod $1\frac{1}{8}$ inch. I informed him that both could be ground without a change either of the wheel or of the work-speed, and he was naturally incredulous. However, it was put to the test. Both sizes were ground efficiently without changing either the work-speed or the wheel, and as the piece of work had to be dealt with only in very small quantities, it was desirable that the work should be treated in this way. Naturally, if larger quantities had to be dealt with, it would have been advisable to have a grade softer wheel to grind a large diameter piston." That brought him to what Messrs. Churchill's manager considered a great point in the argument—that a very wide range of velocities could be obtained without affecting the result materially. It would be interesting if the Author would explain to the Meeting what he had told him privately, because his explanation made clearer than the Paper itself what the Author's views were as to the rate of approach of the wheel to the work. It was the rate at which the actual surface of the wheel entered the work that made all the difference in the comparatively small surface-change of the work. This matter of velocity and its effect upon the reduction appeared to be the whole substance of the Paper.

Mr. Guest, in reply, considered that the works manager of The Churchill Machine Tool Co. was justified in making the statement he did. The condition for grinding, irrespective of output, was expressed by the equation 4 (page 551). According to this, any value of v could be used, provided that the machine could be made to give a

corresponding value of t. As regards this point, he considered that machines were seldom fitted with a sufficient number of cross-feed rates; what was required was a duplicate ratchet which would give finer variations of the feed than the customary quarter-thousandths of an inch on the work-diameter. That was, instead of having one, two, three quarter-thousandths, the feeds might be one-quarter, three-eighths, one half-thousandth of an inch, etc. Messrs. Churchill's manager was correct in saying that the same rate of revolution could be used in grinding the two diameters in question—with corresponding cross-feeds. If a machine maintained so fine a cross-feed as would appear necessary, it would imply that the machine was substantial and well built. What mechanically determined possible fineness of cross-feed was partly the variations of the excessively thin oil-film in the wheel-spindle bearings and partly spring in the machine itself. With a springy machine it was impossible to maintain a fine cross-feed, and had the machine used been one with much spring it could not have done the work satisfactorily.

When taking advantage of this possibility of using a constant rate of revolution over a wide range of work-diameter, it was impossible to satisfy the equation $vt = \frac{b}{c}$ for the range, and accordingly output must be sacrificed. When, as in this case, the amount of work was small, output was justifiably disregarded, and the work could be done at the slower rate. When productive grinding was the matter under consideration, it was necessary to satisfy the second equation, and by combining it with the previous one, the correct work-speeds were fixed.

It would be noticed that the combination made the proper work-speed to depend on the power delivered to the machine. This was one of the reasons why the Author placed a weighted tension idler upon the belt from the counter-shafting to the spindle in his machines. For uniform results, it was necessary to make sure that uniform power could be obtained. A belt which had been tightened, either by taking up or by movement of the cross-slide of the machine, would convey more power than in its previously slack condition; the work-speeds to give the most rapid

(Mr. Guest.)
results would then be slower than previously, and the conditions would vary. A device which maintained a fairly constant power, independent of variation in the belt condition and machine, enabled work to be done efficiently at regular surface-speeds, and generally avoided trouble.

The point raised by Dr. Hele-Shaw was not that usually raised in the shops, although it bore upon the same matter; in fact, these views were directly opposed. The ordinary view was that the surface-speed of the work was the important quantity and was the controlling factor, and was doubled if it were raised from 30 to 60 feet per minute. Dr. Hele-Shaw, however, pointed out that if the wheel were running at 5,000 feet per minute, and the work-velocity was directly opposed to it, the relative velocity had only been altered from 5,030 to 5,060 feet per minute, less than 1 per cent., which was an insignificant matter. This view was correct, and the Author regarded such a difference in the *tangential* velocity as without effect. Comparing a shaping machine and a planer, it did not matter whether the tool moved over the work or the work under the tool, provided that the speed of one relative to the other was the same. Cutting in a shaper at 80 feet per minute would correspond with cutting in a planer at 80 feet per minute. There might be a compound machine in which the work moved at 30 and the tool at 50 feet per minute, and if they moved to meet one another, there would still be a relative velocity of 80 feet per minute and the cutting conditions would be the same.

The variation between 5,030 and 5,060 feet per minute tangential velocity would make no practical difference, and in the Author's theory it was assumed to make none. Considering the bottom corner E in Fig. 2 (page 548) of the arc of contact, it could be seen that there the work had a velocity which was not merely tangential to the wheel-edge, but had a component normal to the wheel-edge, along EA. This normal (material) velocity could be calculated in any case from equation 2, and was the controlling factor in the grinding. If the wheel surface-speed (V) varied, it was the ratio to this of the normal material velocity (v_1) which was the effective quantity (see pp. 564, 565).

The PRESIDENT said he was sorry there had not been more discussion on the Paper. He knew that the Author had given very great attention to the whole question of grinding, and, although he himself was not in the least an expert, he thought he might say with confidence that anyone who had a great deal of grinding to do might trust the Author's opinion as to the manner in which the work could best be done.

Discussion in Manchester.

The CHAIRMAN (Mr. Michael Longridge, Vice-President) in opening the discussion said the way in which the members had received the Paper and the Author showed their appreciation of both. Not very long ago grinding was considered a luxury, only to be employed when extremely accurate dimensions or very fine finish was necessary, but he supposed that, in these days of high-speed lathes and turret lathes, the grinder was almost a necessary adjunct to the first machine. Grinding, so far from being a luxury, was now, he understood, the most economical way of turning out good work. If this were so, the Author had set himself a very useful task, for in a problem where there were so many variables—the hardness of the bond, the size of the grit, the speed of the work, the speed of the wheel and of the feed—he thought it was hopeless for anybody to try to find out by groping experimentally what was the right thing to do. He did not know whether the formulæ given in the Paper were right or wrong; he could not quite follow them; but supposing they were right, or approximately right, they provided means of bringing order out of confusion by correlating all the variables and so enabling one to get a very good idea of the effect of changing each. That was very well illustrated on the discussion of the values of vt and v^2t on pages 553–4. The curves at the end of the Paper were equally valuable.

He hoped the members would not only express their opinion on the Paper, but would also give the results of their own experience.

(Mr. Michael Longridge.)
When the Paper was read in London he was afraid there was no one present capable of discussing it; they had come to Manchester for the opinions of grinders who could give advice based on practical experience as well as on theory.

Mr. HANS RENOLD heartily thanked the Author for bringing forward a subject of such importance at the present time; and no less he congratulated the Institution on having taken steps to have such a Paper read in Manchester. It had been said, and he thought truly, that the quantity of soap used in a country per inhabitant was a measure of the degree to which it had advanced in civilization. No less truly, he thought, could it be said that the quantity of emery wheels used in an engineering establishment, in all its multitudinous operations for removing metal, was a measure which showed whether such establishment was in the forefront of progress or hopelessly lagging behind. In England, he had no doubt, grinding operations in the manufacture of machines were not used to the same extent as one found in America, Germany, Switzerland, or Sweden. Only the previous week he had seen in Zürich some wonderfully accurate and expeditious work done by a special grinding machine, which enabled the Swiss to produce a kind of high quality work unattainable here.

He was rather struck by the boldness of the Author trying to put his experience and practice in the grinding line into such precise and definite formulæ, because his own experience was rather that there were so many constantly altering conditions entering into any grinding operation that no rules, except of a very general nature, could be laid down. Still, if this modern method of removing metal, either in large, small, or very minute quantities, was to be adopted, there ought to be no difficulty in learning how to do it, if the subject were approached in a sympathetic spirit and it was borne in mind that speed, feed, and methods were very different things from what the ordinary mechanic was accustomed to when working a lathe, milling, or shaping machine. A little common sense and power to observe rightly how the results differed when changing the grade of his wheel, its speed, and the feed which

the nature of the work would allow, would help an operator much more than the formulæ the Author advanced so profusely.

In a modern engineering establishment, grinding might be divided into three large groups:—

(1) The sharpening of cutting-tools, such as were used on lathes, milling machines, reamers, or any revolving cutters with two or more cutting edges. Although for sharpening lathe tools a simple grindstone might do, this was no longer the best method when great quantities or accurate grinding of revolving cutters were to be done.

(2) The finishing of hard or soft machine-pieces to a degree of exactitude. By the help of this class of grinding machine, or, as the French more correctly called them, "machines à rectifier," the machinist could now produce machines capable of running at such high speeds as were never possible before the introduction of these finishing machines by grinding. The speaker referred to one such grinding machine in his establishment, which had a grinding spindle running at 120,000 revolutions per minute. It was used for finishing die-holes as small as half-a-tenth of an inch. The grinding wheel, if it might still be so called, was a soft steel wire impregnated with diamond dust.

(3) This group was for doing manufacturing work, where metal was removed by grinding more expeditiously, nearer to size, of a higher finish, and at less cost than was possible by any other methods.

Whilst the Author had tried to give much information by formulæ about wheel-surface speed, work-feed and cross-feeds, for internal and external grinding, the speaker thought that but little use could be made of these mathematical expressions by a grinding operator. All these factors had constantly to be altered according to whether the grinding wheel was soft or hard, of a coarse or fine grain, free or hard cutting. These factors had again to be altered

(Mr. Hans Renold.)

when the work was frail, and could not be well stayed, and would not allow of what was called a full cut. Many grinding machines —in fact, nearly all—were of too light a construction, and full-speed productions could not be obtained. One of the greatest authorities on grinding—Mr. Norton, of the Norton Emery Wheel Co.—was of opinion that there was hardly a formula or rule which expressed the method by which the best and greatest output could be obtained. To obtain this a man with common sense was required, who had great expectations of what could be done by grinding wheels, who was willing to try different methods and combinations of wheels, speeds, feeds, etc., and who was capable of rightly observing the results and adopting whichever he found best. The Author mentioned at the end of his Paper that much depended also upon the correct construction of a machine, whether or not it was stiff and heavy enough to allow a good cut to be taken.

Some twenty-five years ago he (Mr. Renold) had an interesting experience with a Universal grinding machine—one of the best built in those early days—which was perhaps worth mentioning. The emery-wheel stand was on an overhanging knee, cast on a stiff machine body, but still it was overhanging. This machine could never turn out a job as good as desired. One day two iron-stays were made, 2 inches by $\frac{1}{2}$ inch, and this bracket was stayed from the base of the machine. When this was done the machine was much more rigid, and the work turned out was as good as could be desired.

As already intimated, he would like to see more grinding operations adopted, and he hoped that no one present would be frightened by the formulæ given in the Paper. Grinding might, in fact did, at first present some new and often baffling problems; still, if tackled with sympathy and determination, there would be ample reward. Grinding machines worth having could not be made too good, and therefore first-cost cheapness must not be expected from this type of machine.

Before he left his works that evening, he had procured a few figures which might be of interest to some of the members

present. These figures were apropos of the proportion of the number of grinding machines to those of ordinary machine-tools used in his works. In his factory there were 980 machine-tools, of one kind and another, and, along with those, there were 147 grinding machines. This gave, for every 100 machine-tools, 15 machines on which metal was removed by the help of a grinding wheel. These 147 grinding machines grouped themselves about as follows:—

One third for sharpening cutting-tools.

One-third for rectifying and finishing tools and machine parts.

One-third for manufacturing machine parts, namely, removing metal.

He thought it might be news to some of those present that in Birmingham there was a large firm which finished the 3·3-inch shells by grinding instead of turning in the ordinary way in a lathe. Broad emery wheels were used, and shaped exactly to the form of the shell, including the nose. It was claimed that by this method better and quicker work was done. He thought that this was a claim on behalf of grinding which he could hardly support, especially when the rough finish required for a shell was considered.

In manufacturing grinding operations, such as making highly-finished calender bowls for all sorts of purposes, also grinding of railway axles and wheels, rolling-mill rolls, etc., large grinding wheels were now used, even up to $2\frac{1}{2}$ and 3 feet diameter and 12 inches wide. Such wheels were mostly driven by special motors mounted on the grinding spindle. The more usual-sized wheels of 14, 18 to 24 inches in diameter for doing heavy manufacturing work could seldom give the utmost production when driven by a leather belt, however wide it was made. In his own works some twenty specially constructed wet grinding machines, of different sizes, could not be made to give the best work and in greatest quantities until all medium and larger machines were driven by chains; so that the speeds of these chains could be kept within reasonable limits, the diameter of the grinding wheels was kept fairly large.

(Mr. Hans Renold.)
Mr. Guest, in his formulæ, warned them not to make the wheel-speeds too high, but he (Mr. Renold) had never found any difficulty from wheel bursting at very high speeds. A grinding wheel well bonded, free cutting, reasonably used, and above all carefully and truly mounted, would stand a very high surface-velocity. A still higher speed could be given to a compound wheel made of a series of sticks fixed into a circular steel ring in such a way that the higher the speed the more these sticks would wedge into their places, where they were thoroughly supported in a cradle. A grinding wheel thus made could run 50 per cent. higher than a solid disk-wheel. Such a compound wheel had clearing spaces between the sticks and could do more heavy work than a solid wheel. The chips came off like fine turnings, looking like a bunch of fine waste. Such work could only be done when everything was right. The power must be there, the wheel-speed right, the water plentifully supplied, the work-feed right, and the machine stiff, and all gliding and running fits accurately made.

The power required for a grinding wheel might be anything from one-tenth to 20, 40 and even 100 h.p. He (the speaker) had seen, some three years ago, a machine for grinding railway-axles, with the chilled wheels ready mounted, and some four grinding wheels were at work at the same time. There was about 250 h.p. on this grinding machine. To drive light ordinary size grinding machines, there was no difficulty with well-jointed leather belts, but when 14, 18 or 24-inch diameter wheels by 2 or 3 inches wide were used, as often was the case for manufacturing purposes, then no better medium than chains could be found for driving. With such a drive, the power and speed, once provided for, was there and could be depended upon whether the grinding cut were heavy or light. There was no rise in the temperature of a running spindle caused by the slipping of a leather belt, and therefore the bearings could be made a much better fit, without which no grinding machine could possibly give good results.

The Author also alluded to the glazing of grinding wheels depending upon the speed of the wheels. He (Mr. Renold) could not altogether agree with the Author on this point. He always

understood that the speed might be quite right, still glazing would sometimes take place. Such glazing would be caused by the used-up particles of the wheels not falling away or wasting fast enough—that is to say, after the wheel grains had done their work and lost their sharp cutting corners, they should break off, and the wheel present fresh sharp-cornered grains to the work.

Mr. W. H. Cook, referring to the remark of Mr. Renold about the rarity of grinding correctly, said he could mention the name of a firm in the district where grinding had been done for very many years as accurately as in any part of the world. He had seen, some years ago, two large diameter rollers 100 inches long, which, after grinding, were pressed together, the ends being made up with clay to form a well, and water then poured in, and there was not the slightest trace of the passage of water between the two after several days. This was a fine test.

He was of the same opinion as Mr. Renold, that if too much notice were taken of the mass of formulæ, any one who had had no experience of grinding machines would be inclined to say it would use up too much of his brain power to install it, and he would therefore do without it. Fortunately, he had had considerable experience in the use of grinding machines, otherwise he might say the same himself. There were some people to-day who were advocating the use of grinding machines to remove heavy masses of material; he himself had never known such a procedure to pay, either in time or general financial results. The best course to pursue was first to have lathes of sufficiently heavy design, particularly in the front necks of the fast head, and to turn the work as near true as possible, leaving a few thousandths of an inch for the grinder to finish true and correct to size.

In the Manchester district certain machine parts had been ground in very large quantities per week for more than thirty years at a low price, exact to diameter, and with a satisfactory finish, and in dealing with one of the works doing this his experience had been quite different from what was stated in the Paper. In many cases it was found that whatever change was

(Mr. W. H. Cook.)
made in speed or feed the wheels would glaze or wear unduly; it was only by making continued experiments with different kinds of wheels and with varying speeds and feeds that the best results were obtained, and then no changes were allowed, no matter how cheaply other wheels could be bought.

Another difficulty he had experienced was the jars in small castings arising from the method of suspension. He had never found satisfactory work with one centre revolving and the other fixed; both should be dead centres. There were other difficulties which arose, but after a time experience showed how they should be overcome. One great reason why grinding was not more generally adopted, except in very high-class work, was the high price of the machines. When a machine which could be carried on one's shoulder cost from £80 to £100, the question of its adoption became prohibitive in many instances, and it would be to the interest of some maker to design a machine which would suit the general trade at a more reasonable price. In concluding his remarks, Mr. Cook asked the following questions: (1) How could Mr. Guest's formula apply to two wheels of different composition? and (2) Would he use the same formula for all kinds of materials —brass, cast-iron, or steel?

Mr. H. H. Asbridge said that, as one who had been interested for some years in the manufacture and design of grinding machines of the type referred to in the Paper, he would like to make a few remarks. In the first place he would like to thank the Author for his courage in bringing the subject forward, more particularly in view of the scarcity of data relative to it. He had read the Paper carefully and followed the theory as developed, and he thought that a more correct title would have been "The Theory of Grinding, geometrically considered." There was no doubt it could be conceded to be correct when viewed from the geometric standpoint as to the interaction of the wheel and work-surfaces shown in diagram form in Fig. 2, and so ably analysed by the Author, always assuming, of course, that there was interaction—that was, a definite amount of cut or reduction of work-diameter.

In order to develop his theory, the Author had had to assume certain factors as constant, those being the material operated upon and the grinding wheel. Admitting that these were constant in individual cases, and following the theory to its logical conclusion, one would have first to find the best and most suitable surface-speed or velocity of work, also the maximum cross-feed the work or the wheel would stand. This, of course, was done in actual practice. When those two factors were obtained, equation 4 (page 551) was formed. Using this as a basis, the correct work-speed and cross-feed for other diameters of work could be calculated as in equation 5 (page 555) and examples given on page 556. Considered geometrically from the basis of the constant area of ground-away portion, due to the interaction of wheel and work, it might be correct, but it was not borne out in practice.

Even if it were admitted that the work-speed should be varied proportionately according to its diameter, there was always present the danger of vibration in heavy large-diameter work, which was difficult to control. Conversely, in the case of small diameter work it was essential to have a higher work-speed than that given by equation 5, in order to distribute the stress of the wheel-cutting action, and also—what was more important—to distribute equally throughout the ground portion the excess heat generated and not carried away by the cooling water.

Why should the Author, in developing his theory, adopt the basis of variable work-speed and proportionately variable cross-feed when, by keeping both those factors constant, the same effect could be produced? It should not be assumed from this that the constant work-speed must be absolutely invariable, but the word constant was used relatively in combination with a certain grade and speed of grinding-wheel, and as determined, it would be constant over a certain range of work-diameters, as the primary governing factor in the adoption of any work-speed was the grinding wheel, and the work-speed might be anything from, say, 20 to 100 feet to give efficient production.

If reference were made to the Table on page 556, wherein pieces of work of 1 inch, 4 inches, and 16 inches diameter were

(Mr. H. H. Asbridge.)
compared, using the same diameter of wheel, the 1 inch and 16-inches being deducted from the 4 inches diameter basis, and which might be taken to be correct practice, it was found on working out the examples that the cubical contents of the material removed per minute were practically identical in each case, and, viewed from that standpoint, could be taken as proving the theory or the formula to be correct. But, examining the examples given from the practical standpoint, the 1 inch piece of work could not be ground successfully at 9 feet per minute with 4 thousands in diameter cross-feed. The machine and the grinding wheel would stand it, but the work would be distorted.

If they examined the examples further, and assumed a constant work-speed of 30 feet per minute, and a constant cross-feed of $1\frac{1}{4}$ thousands on diameter, they found that the cubical contents of material removed per minute were exactly the same as given in the Table, but there was this difference, that the 1 inch piece of work could be successfully ground at 30 feet per minute with $1\frac{1}{4}$ thousands cross-feed, because at that speed the heat generated could be better distributed and dissipated. In order to prove that, he had prepared two sample shafts 1 inch diameter by 12 inches long, one being ground at 10 feet per minute and 4 thousands diameter cross-feed, and the other ground at 27 feet per minute at $1\frac{1}{4}$ thousands per diameter cross-feed. These speeds were the nearest obtainable on the machine. $\frac{1}{32}$ inch diameter was ground from both shafts, the traverse being the same per revolution of work. Both shafts took four minutes each, and both took 5 h.p. net. The inspector's report on the shaft ground at 10 feet was as follows:—

"Shaft discoloured and shows deep traverse lines 0·002 big in centre."

On the shaft ground at 27 feet:—

"Finish fairly good, shows slight traverse lines and 0·002 large in centre."

This test showed that while both shafts had been subjected to the same work in the same period of time, the higher work-speed came out best, and if a still higher work-speed had been used with a proportionately smaller cross-feed so that the same amount of

material was removed in the same time, the result would have been better. Both tests were made on a powerful machine, and under a flow of water of 40 gallons per minute. That might or might not be taken as conclusive that the theory of grinding should be developed on a basis of constant work-speed and constant cross-feed in order to maintain a constant production, but it indicated that it was logically the correct method. (*See* page 587.)

Professor A. B. Field said he had not had an opportunity of giving to the Paper the consideration it deserved; but he felt that he was justified in congratulating the Author upon running the gauntlet of criticism and introducing the formulæ. After all, if a great deal of trouble had to be resorted to, to get the best results, it was one step gained to have a guiding line, to enable the practical results to be properly co-ordinated and compared. From that point of view, it seemed to him that an investigation of this kind should be most useful.

He would like to ask whether the question of the heating of the work would not sometimes limit the considerations that Mr. Guest brought forward. The general heating of the work was small in this class of machining; but, on the other hand, with heavy cuts and comparatively small work-speeds, local heating might occur, and, in consequence, small distortions of the work; thus the final piece, particularly when unsymmetrical, would be affected by these temperature changes. He imagined that considerations of this sort would influence the formulæ, and that really the Author was simply aiming at a general guide to the relations of speed, time of cutting, and so forth.

With regard to the ultimate bursting strength of the disk, it would be interesting to hear from the Author, or other practical grinders, whether the relations that usually obtained in the case of a rotating disk having some ductility held similarly in the case of such a bonded material as these corundum wheels. Burst wheels were doubtless rather rare, but the information obtained from such cases, where the bursting was not due to flaws, should be of value.

Mr. Guest, in reply, said that the particular value of grinding was that it produced accurate work economically which was useful for two reasons: first, that it gave very much better wear, durability, and running in the product; and secondly, that it saved erection costs considerably. In making press and running fits along the same shaft there was little doubt as to the saving effected by grinding. Mr. Hans Renold had pointed out that in the case of a cup-wheel very long chips were produced. Disk-wheels could not produce long chips, as the chip-length was controlled by that of the arc of contact which was always short, but with a cup-wheel the chip-length could be almost half the circumference of the wheel, and one of the smaller difficulties in cup-wheel machines used for manufacturing was that the chips formed a swath which was rather difficult to get away freely; it was like steel wool, and if the spaces in the machine were not large, clogging was apt to occur.

Glazing, as Mr. Renold said, was due to the rubbing down of the fine projecting points of the wheel-surface. This was taken for granted in the Paper, the cause being assigned to a too small normal material velocity. The wheel consisted of particles of abrasive held in cement, and looking at the surface of a modern wheel one saw that it was comprised of particles, between which were comparatively deep hollows, within which were other particles. In the action an outside particle encountered the work along the arc HE, Fig. 2 (page 548); at H it merely rubbed, but at E it cut heavily. The particles a little lower in the wheel than these rubbed at points such as Q, then cut a little, but did not take such large cuts as the outer particles. After a while the outer particles would be broken or torn out of the wheel, and the full action would be taken up by the next set, but the previous action would have already dulled the points of these somewhat. If the force produced at E were insufficient to dislodge the outer particles, they would gradually become more blunt until the surface of the wheel was comprised of polished facets and looked shiny. It was then quite glazed and would not cut. There was a certain amount of energy stored in the machine and wheel, and by suddenly increasing the cross-feed it could be utilized to break up the face of a glazing-

wheel. When it was observed that a wheel was beginning to glaze, that should be done immediately and the work-speed then lowered. It was necessary to do this before the glazing was in an advanced stage, else the wheel-surface would be so smooth as to prevent the course being effective.

Mr. Renold mentioned that sometimes the wheel got clogged up with material from the work, and referred to this as glazing. It seldom occurred, and was technically termed "loading." The tendency was greatest with copper and such tough materials, and the best course was to rotate the work fast, taking a light cut.

Mr. Cook also referred to difficulties caused by glazing. If the wheel were quite unsuitable, it was necessary to change it. More power was needed for the use of a hard wheel than for a soft one, but the harder wheel would last longer and would do more work as each particle had to be blunted more before the cutting force tore it from the wheel. The hard wheel itself would thus be the cheaper if wheel price alone were considered; including power cost there was little difference, the further inclusion of labour costs generally showed the softer wheel to be the more economical. The growing use of such wheels was another reason why modern machines tended to use slower work-speeds. The seller would use and offer the softest wheel he could, so as to obtain the greatest output from the machine. The worst feature of the use of hard wheels was the greater heating effect.

Mr. Cook then referred to vibration, and said that it might be stopped by changing the wheel. Vibration effects were difficult to treat; they almost invariably arose from some rapidly rotating part being out of balance. The forces produced by a small want of balance in the wheel were considerable, because of the high speed; thus a want of balance of one ounce at a foot at a speed of 1,200 r.p.m. caused a force of about 30 lb. weight, changing its direction twenty times a second. If there were any period of free vibration in the work or machine approximately the twentieth of a second, the force would have a cumulative effect and soon produce marked results These vibration effects were important in all high-speed machinery; the shafts of some fine woodworking machinery upon which the

(Mr. Guest.)
Author was engaged had to be balanced to a quarter of an ounce at six inches. As want of balance in a wheel might so easily produce vibration, changing such a wheel for a balanced one should be tried when vibration gave trouble. Wheels were frequently balanced by the makers by the insertion of lead at the central hole. The wheel would then run well until worn so that the defective part was removed, when it would be out of balance. When a firm used a large number of wheels, it was well to balance them on ways occasionally.

He preferred to refer Mr. Cook's statement as to the prices of machines to someone else; but he did not think it possible to build such accurate machinery cheaply. A machine which would regularly give the accuracy demanded in modern manufacture must be very well built, and the question was whether it would pay at the price asked for it. It seemed to him that if the work were produced rapidly by comparatively unskilled labour without any trouble, the price of the machine was a secondary consideration. The cost of labour and delays were the principal items in manufacturing expenses.

Mr. Asbridge inquired as to the effect on the equation of variations in the material ground and of the wheel, and he appeared to think that the formulæ applied to some definite material and wheel only. A formula bearing upon any physical phenomena would contain certain constants (such as the gravitation constant) dependent upon the particular case. To cover the changes of work and wheel material, two constants might be expected to be necessary, but actually only one was needed—a in equation 4 (page 551). All variations, both of work and wheel material, were covered by changes in this constant. In all, three constants were used: in the second equation there were b, which was proportional to the power used (but its value was affected by the grade when the wheel was changed), and c, the traverse or width of wheel—for in grinding practice the amount of traverse must lie between $\frac{5}{8}$ and $\frac{7}{8}$ of the wheel-face, otherwise the wheel would wear convex and produce on the work a very shallow helical track, the appearance of which was objectionable. The constant a depended only upon the material of the work and upon the wheel substance; for cast-iron it had a value rather more

than twice as great as for steel, and if the wheel used were changed for one a grade harder, the value of a would be lessened from 10 to 15 per cent. Thus a was a definite constant when any particular material was being ground by a wheel of a certain material and quality, but its value changed when either wheel or work material was altered. By this variation the formulæ applied to all cases.

The results of the two trials on grinding 1-inch bars showed that the value of a in the case was such as to make the higher work-speed the more suitable of the two tried, but they were insufficient to ascertain the best value of the constant. At the slower speed the work was burned, which showed that the wheel was glazing. This supported the Author's theory, as it showed that raising the work-speed and reducing the cut, keeping the output constant, checked glazing.

Mr. Asbridge thought that the Author's theory was geometrical only, but this view was erroneous, and probably arose from the Author's separation (page 545) of the geometrical and mechanical sides of the problem. The intimate connexion of these views and the interdependence of the geometry (pages 546, 548–9), and the force effects (pages 547, 550–1) involved, lead to the theory advanced. The geometrical motion determined the sectional area of the chip taken by the points of the abrasive particles, this area determined the force upon the particle, this force determined whether the particle was going to be broken or torn out of the wheel, or whether it would remain in it and glaze, and thus the whole action was determined. If the theory were geometrical only, geometry alone would be necessary for its absolute proof.

Mr. Asbridge stated that he upheld the usual view that the work-surface speed should be constant, and asked, "Why develop a theory upon the basis of variable-work speed and feed?" This question indicated a misconception of the nature of the Paper. To take any variable (or constant) work-speed as a basis would not be a theory, it would be termed an assumption—it might be a useful one. Such was the common view that the work-speed should be constant. It was the failure of this assumption to meet the

(Mr. Guest.)

case that first led the Author to investigate the matter. Any physical theory must be based upon the known properties of the bodies employed; to obtain workable theories, properties or actions having small effects have almost always to be neglected. This was the case in that set forth by the Author, and upon some of these points he had particularly desired the opinions of those present. Proceeding thus from certain bases, the Author arrived at the conclusions as to work-speed which were given in the Paper—that is, the work-speed rules were not assumed but rationally deduced.

As regards the vibration of heavy pieces of work, this was a phenomenon usually regarded as mysterious in the shops. The vibration of slender pieces, having a comparatively slow free period, seemed to most a natural occurrence. The vibration occurring with heavy pieces of work was due to the slowing of a free vibration period in the combination of machine and work, by the increase of the mass of one portion—the work. When the period approximated to a forced period there would be appreciable vibration. The effect produced upon the vibration period of a shaft by fixing a heavy pulley at its centre, and the lowering of pitch of a tuning fork by weighting the ends, were examples of this lowering of periods by the addition of mass.

Professor Field asked about heating the work; it was an important point. The work was heated all the time and just at the surface was raised to a high temperature. Calculation and the examination of the chips showed that fusing of the metal occurred when the cut was heavy, and the Author considered that to be the chief reason why there was so little difference between grinding steel when it was hardened and when it was soft. It was sometimes found that the surface of ground hardened steel was not as hard as it should be; if this were due to loss of temper in grinding, the careful removal of a few thousandths would reveal a surface of the correct hardness. All hardened work should have the last few thousandths ground off with a very fine feed, for this reason.

In precision grinding the bursting of a wheel was an exceedingly rare occurrence, and the accidents had almost invariably been

traced to some damage to the wheel not arising from its normal use. The value of Poisson's ratio for wheel material was not known, and so strength formulæ involving it were not applicable. The dimensional proof (in the Author's book) that the stress depended upon the peripheral velocity only, took the wheels to be of similar shape, but the approximation was near enough for practice. The strength and permissible speed increased with the harder bonds (*see* page 588).

Communications.

Mr. H. H. Asbridge wrote that, since speaking at the Meeting he had carried through some further tests, with a view to determining the best work-surface speed over a range of shaft diameters from $1\frac{1}{2}$ inch to 6 inches, under as nearly as possible constant conditions, and regardless of finish obtained. The tests were carried out on a self-contained electrically-driven Churchill plain grinding machine, and, specially for the test, both the work and the wheel were driven by independent motors connected with large ammeter dials reading directly in horse-powers, the intention being to record the power used on each. It proved, however, that the difference between the work-drive, when running light and when cutting, even on the large diameters, was so infinitesimal that it was neglected.

The method adopted to keep the cut constant was to bring the wheel directly on to the work, and operate the cross-feed so as to maintain the horse-power constant during the period of the test, the figure determined upon being 10 h.p. over that required to drive the wheel when running light; 30 h.p. was available, but a maximum reduction was not aimed at. No traverse motion was used. The work-surface speeds aimed at were 60, 40, 20 feet respectively, but as these could not be obtained exactly on the machine, the nearest possible were used. All the tests were carried out in duplicate, the grinding wheel being frequently trued to maintain as constant a condition of face as possible. The results were given in the accompanying Table, the material removed being

(Mr. H. H. Asbridge.)

the average of the tests. The efficiency was also given both for each diameter of shaft in relation to the surface-speed used, and the material removed, and also for the range of shaft diameters.

It would be noticed that the efficiencies on each test were the highest for the highest work-speed adopted, and were very consistent throughout the range, the 4 inches diameter being the lowest; the efficiencies for the slowest speeds fell consistently as the diameter of work increased, and would indicate that the work-speed for small diameters had very little effect on the ultimate result, but the higher speed would be preferable for reasons mentioned earlier. On the larger diameters the correct work-speed was evidently of much more importance, and a surface-speed of 60 feet per minute or over would apparently be the most efficient. It would be interesting to have the Author's comments on the results tabulated.

Grinding wheel: 26 inches diameter, 3 inches wide. 6,000 feet per minute surface-speed. Work-surface speeds: 60, 40 and 20 feet per minute. Mild steel shafts: 0·35 car.

Diameter of shaft tested	$1\frac{1}{2}$ in.	2 in.	3 in.	4 in.	6 in.
Surface-speed feet per min.	42 31 23	56 42 22	63 33 19	61 44 19	65 38 22
Revolutions per min.	106 80 58	106 80 42	80 42 24	58 42 18	42 24 14
Material removed cu. in. per min.	1·067 1·04 1·04	1·047 1·047 0·958	1·037 0·944 0·756	0·93 0·81 0·67	1·051 0·771 0·507
Net h.p. absorbed by cut only. Maintained during test	10	10	10	10	10
Efficiency per cent. for each diameter of shaft	100 97 97	100 100 91·5	100 91 73	100 87 72	100 73·3 48·2
Efficiency per cent. over the range of shafts	100 97 97	98 98 89	97 88 70	87 76 63	98 72 47

Mr. Guest wrote that, with regard to Mr. Asbridge's interesting tests on work-speeds which he had made since the Manchester

Meeting, some deduction could be made. Owing to the type of feed used, the wheel being fed into the work by hand, individual results might be somewhat out, but the general conclusions would be correct. When the wheel was thus fed, keeping the power constant but neglecting wheel-wear, the rate of removing material would depend upon the state of the wheel, whether it were glazing or wasting, in the following manner. The more it was glazing the less material would be removed, but when the wheel was keeping keen by wear, there would be practically no difference whether it were only just wearing normally or wasting considerably. Thus if the relative efficiency were high—say over 95 per cent.—all that could be deduced was that the wheel was not glazing, but to what extent it was wasting could not be determined. Accordingly, these tests determined the point where glazing began.

The results were summarized in the last lines entitled "efficiency per cent. over the range of shafts." Considering the lowest line first, it was clear that at a work-surface speed of 20 feet per minute, the efficiency fell off regularly as the diameter increased; this applied also to other speeds, and was clearly a general law, for there was no particular virtue in any one speed. At the 20 feet per minute, a 10 per cent. (nearly enough) drop occurred at 1½ inch diameter, the efficiency falling from 0·97 to 0·89 with the diametrical increase from 1½ inch to 2 inches. A 10 per cent. drop first occurred in the 40 feet per minute series at 2 inches diameter (0·98 to 0·88), and in the 60 feet per minute series at 3 inches diameter (0·97 to 0·87), so that these might be taken to be corresponding diameters at the various speeds. If the experimental results were plotted into curves, with the material removed and the work-diameter as ordinates and abscissæ respectively, the shape of the curves would be similar to steam-engine diagrams—the admission period corresponding to wheel-wear and waste, and the expansion line to the glazing, the cut-off being the glazing point.

Probably the best speed to run at is just at the glazing point, of which 2-inch diameter work at 40 feet per minute was representative. According to the Author's theory, work of greater

(Mr. Guest.)
diameter than 2 inches would glaze at 40 feet per minute. As an example, consider the case of 6-inch work running at this speed. Equation 5 (page 555), inserting the values from the 2-inch diameter experiment, gave

$$42 = \frac{ac}{b} \times \frac{2 \times 26}{2 + 26}, \text{ so that } \frac{ac}{b} = \frac{42 \times 28}{2 \times 26} = 23.$$

Taking the values for 6-inch diameter work gave

$$\frac{ac}{b} = \frac{38 \times (6 + 26)}{6 \times 26} = 8.$$

Since b and c were the same in the two cases, a had been reduced to $\frac{8}{23}$ of its previous value, so that the wheel would glaze according to the theory. This was typical of the whole change indicated by theory, which gave such a fall as was indicated by the experiments.

Taking the same experiment—2 inches diameter at 42 feet per minute—let it be asked at what diameter work moving at 60 feet per minute should be on the glazing point. Substituting in equation 5, it now gave

$$60 = \frac{ac}{b} \times \frac{d \times 26}{(d + 26)},$$

and $\frac{ac}{b}$ has the same value (23) as previously found;

$$\therefore\ (d + 26)\,60 = \frac{42 \times 28}{2 \times 26} \times d \times 26, \text{ or } d = 3 \text{ inches nearly.}$$

In the same way it could be found that, at 20 feet per minute, work of 0·9 inch diameter would be at the glazing point. Comparing these calculations with the points previously noted in the experiments at which the 10 per cent. drop first occurred, the correspondence was close enough to strengthen belief considerably in the reliability of the Author's theory.

The experiments established the fact that a work-speed of 40 feet per minute worked perfectly on material of 2 inches diameter, but failed more and more with increase of work-diameter. This constituted a definite proof that the usual assumption, that the work-surface speed should be constant, was incorrect.

THOMAS HAWKSLEY LECTURE.*

THE WORLD'S SUPPLIES OF FUEL AND MOTIVE POWER.

By DUGALD CLERK, D.Sc., F.R.S., *Member of Council*, of London.

Dr. W. Cawthorne Unwin, F.R.S., *President*, in the Chair.

Friday, 29th October 1915.

In the first Thomas Hawksley Lecture, the late Mr. Ellington dealt very ably with Water as a Mechanical Agent, a subject to which he had devoted a highly successful life's work.

In the second Lecture, the late Mr. Bryan also dealt with an important hydraulic branch—Pumping and Waterworks Machinery, a field in which he had established an unrivalled supremacy. It is not open to me to deal authoritatively, as my distinguished predecessors have done, with hydraulic engineering. My main study for over thirty years has been the internal-combustion engine in all its various forms, and my experience in design and construction has been mainly acquired in that field. I cannot, therefore, aspire to follow the early Thomas Hawksley Lecturers by confining myself exclusively to hydraulic engineering.

Thomas Hawksley's Definition of Hydraulic Engineering.—Thomas Hawksley, however, was a hydraulic engineer in the very widest sense, and he defined hydraulic engineering very neatly in his Presidential Address to the Institution of Civil Engineers in 1872.

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* First Thomas Hawksley Lecture, by E. B. Ellington, Proceedings, I.Mech.E., 1913, page 1215. Second Lecture, by W. B. Bryan, 1914, page 811.

He there stated: "This branch of engineering embraces, and for the most part restricts itself to, the practical application of those of the physical sciences which relate to the properties, conduct, and treatment of fluids, whether inelastic or gaseous." Hawksley was not only a water engineer, but a very distinguished gas engineer; and in hydraulic engineering he included work dealing with gases as well as liquids. Indeed, his idea of hydraulic engineering was much wider than that adopted by professional men of to-day. Following the broad definition given, he said: "It therefore comprehends within its scope the provision and distribution of water and gas for the supply of towns; the collection, conveyance and utilization of sewage; the employment of atmospheric air as a means of impulsion in tubes and for the ventilation of mines; the improvement of rivers and estuaries; the reclamation and defence of land from the sea; the drainage of fens, and the collection and application of water for use in irrigation; and it even renders its assistance to the determination of the suitable form, and the amount of mechanical power, to be given to a ship to enable it to fulfil the conditions imposed by the requirements of commerce and the necessities of war."

Comprehensive, however, as this definition was, Thomas Hawksley's life showed that for him it was all too narrow. Thus, in 1845 we find him at The Institution of Civil Engineers discussing the conditions of working of the Atmospheric Railway, and using his mathematical ability with good effect, he came to the conclusion, shown by late experience to be correct, "that the atmospheric principle was inapplicable to long sections of tube, and therefore was generally inapplicable to the traffic of a long line."

In 1864 we find him appointed the first President of the British Association of Gas Managers, and keenly interesting himself in the Papers then read, including one on "The Application of Gas as a Motive Power," by Mr. Goddard, of Ipswich. This Paper described the explosive gas-engine of Lenoir, as built by the engineering firm of Barrett, Excell and Andrews, of Reading. and the discussion showed that even then the gas managers were alive to the desirability of developing a day consumption.

Hawksley's Advice to Plan in Advance for Peace and War.—In 1872 he became President of The Institution of Civil Engineers, and in addition to the notable definition of Hydraulic Engineering just given, he urged in the same Address the necessity of preparing for war in times of peace, by designing and building suitable ships, weapons, and munitions. He favoured small high-speed war vessels for commerce protection, and advised members of the Institution to devote themselves to the subject. He would have been delighted with the fast cruisers and torpedo-boat destroyers of to-day, with their speed of 30 to 36 knots, only made possible by steam-turbines developed by Sir Charles Parsons.

Referring to the Franco-Prussian War, he said, "and we have learnt that, in the case of otherwise equally matched antagonists, the victory has been realized by the combatant that was the best provided with the weapons and munitions which, notwithstanding the existence of Government arsenals, had been devised in, and had been largely drawn from, the offices and workshops of the non-military engineer."

Fortunately for us, the great British fleet of to-day has proved itself to be overwhelmingly superior to that of the enemy, and it has been developed by the joint efforts of men like the late Sir William White, Sir Philip Watts, Mr. Tennyson D'Eyncourt, and Admiral Sir Henry Oram on the official side, with non-military engineers like the Hon. Sir Charles Parsons, Sir John Thornycroft, Mr. Yarrow, and many others. Our fleet has also given us time to prepare a large army and supply it with the best weapons and munitions.

In 1876 Hawksley became President of the Health Department of the National Association for the Promotion of Social Science, and in that year he delivered a remarkable Presidential Address at Liverpool, in which he discussed the growing population of England and Wales, and proved that at the then rate of increase, allowing for emigration, 24,000,000 in 1876 would become 42,000,000 in 1918, and at the end of the fifth generation, at the termination of the twenty-first century, 400,000,000, an obviously impossible population for so small a country. Even in 1876 he feels concern for our position, England and Wales having one

person to one and a quarter acres of its 30,000,000 acres of cultivable land, while the other kingdoms of Europe had about five acres of land to each person.

He pointed out that 40 per cent. of the most important articles of food of the people was imported from abroad, and in view of this he said: "Now I ask you, as earnest sociologists, whether a nation can in the proper sense of the word truly say of itself, 'I am great,' so long as it is unable, if need be, to maintain itself? I look, indeed, with alarm to the signs of the times, the general restlessness of European nations, and the possibility of our being entangled in a war . . . for, without in the least doubting the powers of England, and her ultimate ability to come with glory from the fray, I cannot avoid expressing the apprehension that our supplies of food from abroad may be for a time very seriously interfered with, if not wholly interrupted . . . let every patriotic sociologist beseech our Government to look well to its Navy, with the object of maintaining our old command of the sea, and for ensuring the protection of that mercantile marine without which there can be neither health nor happiness for the multiplying millions of this country."

Hawksley's fears for the immediate future of his country proved unfounded, prosperity continued to increase, although he thought "we have thus damaged, I think, irretrievably, our manufacture and commerce . . ." and our country was never more prosperous than in the middle of 1914, when the Great War burst upon us. Hawksley, nevertheless, saw clearly the essentials of success, an overwhelmingly strong navy, a powerful and well-equipped army, and a brave and willing people, willing and eager to fight for liberty, and ultimately to overflow to our ever-increasing over-sea dominions, in answer to the cry, "Space, more space."

Thomas Hawksley had interests not only in hydraulic engineering, however widely defined, but in the welfare of his country, and an intense desire to see it prosperous and happy in the future also. I am, accordingly, encouraged to deal with the vital question of fuel and motive power in the wide manner which would have been adopted by Hawksley.

*Industrial Civilization requires Coal, Oil, and Motive Power.**—The present civilization of the world rests upon a basis of coal and oil fuel, and water, steam, and internal-combustion motive power. At the middle of the eighteenth century the United Kingdom had but the small population of ten and a half millions. It was only entering into the stage of transformation from a purely agricultural country to the first great industrial community of the world. Previous to that time motive power had only been available to a small extent, as provided by water and wind. True, the Newcomen steam-engine then existed, but its use was strictly limited. In the third quarter of that century the work of James Watt raised steam-power from a wasteful process to a relatively economical one; and in the first instance the early Watt engines were entirely used for pumping out mines. The development of the steam-engine by Boulton and Watt was thus continued, and necessitated by the needs of the hydraulic engineer.

The coal consumption of Newcomen's engine was about 20 lb. per i.h.p., while that of Boulton and Watt was from 5 to 7 lb., about one-fourth to one-third of the pioneer engine.

Engineers' later efforts greatly improved upon these figures; thus triple-expansion engines require 2 lb., large steam-turbines $1\frac{1}{2}$ lb., and suction-gas engines 1 lb. per i.h.p.

The success of the Watt steam-engine enabled coal-mining to be firmly established and coal output increased; and this increase of output was accompanied by the rapid invention and application of numerous mechanisms and processes leading to the plentiful production of iron, steel, textile fabrics, chemical manufactures—soap, alkali—the whole mechanism, in fact, required for the existence and comfortable subsistence of the rapidly increasing population of

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* Just before delivering this Lecture, my attention was called to an able work entitled "Natural Sources of Energy," by Professor A. H. Gibson, D.Sc., *Member*, of the University College, Dundee. This interesting work was published in 1913, and in it is discussed the problem of the fuel and motive power of the world in a careful and comprehensive manner. The results given here agree generally with Professor Gibson's conclusions, although arrived at independently from somewhat different data.

these islands, which in 1801 had risen to over fifteen and a half millions.

The steam-engine was rapidly applied to stationary purposes, driving mills and works of various kinds, then to marine engines, and last of all to land locomotives, and by the middle of the nineteenth century in its reciprocating form it had firmly established itself as the greatest source of motive power for man's use. The low cost of coal and the large amount of power obtained from steam for small capital and running expenditures at first made it unnecessary to think of economizing too closely. As time went on, however, the amount of power required rapidly increased. For example, at the beginning of the nineteenth century the steam-power developed in stationary engines in the whole kingdom did not amount to more than 4,000 h.p., and even in 1836 an engine developing 40 h.p. was considered a very important undertaking. In 1836 this power had risen to about 30,000 h.p.

The Committee of Managers of the Birmingham Philosophical Institution published a report on 3rd October 1836 which gave, among other things, a statement of the steam-power employed in Birmingham in 1835; it amounted in all to 2,700 h.p. divided among ten industries, and employed 4,000 men and 1,300 women.

Total Power of Industrial Engines in Great Britain in 1907.—In the first census of production for the year 1907, the total power of industrial engines in use in Great Britain and Ireland is given as 10,578,475 h.p., and the steam-engine power of road rollers and road locomotives owned by public authorities amounted to 167,192 h.p. Of the industrial engines, steam reciprocating engines were rated at 9,118,818 h.p.; steam turbines, 530,892; internal-combustion engines, gas, oil, etc., 680,177; and water power, 177,907 h.p. The persons employed in the factories using this large power numbered nearly $10\frac{1}{2}$ millions; so that, roughly, the power available for the industries of Britain was nearly 1 h.p. per person employed. To support the 46 millions of people now living in the United Kingdom thus requires a continuous enormous expenditure of power, and a very large consumption of fuel.

The total coal known to be in existence in the world is given by Mr. D. B. Dowling as 7,397,553 million tons, and the total output of the whole coal of the world in 1913 was 1,363,878,110 tons. Assuming that rate of consumption to continue, obviously we have over 5,400 years' supply.

The Report of the Royal Commission on Coal Supplies, issued in 1905, as the result of an elaborate investigation, gives the contents of the proved coal-fields of the United Kingdom as 100,000 million tons, and estimates coal in still unproved fields as 40,000 million tons. If one can assume them to realize 25,000 million tons, then at the present yearly consumption of 250 million tons we have still 500 years' supply.

In the year 1903 the output of coal from Britain was, in round numbers, 230 million tons. Of this, about 168 million tons were consumed in the country and 62 million tons exported. Much of this exported coal, however, was used for coaling purposes for British steamers abroad. Under these circumstances it becomes highly important to the country at large, and very interesting to the engineer, to consider what can be done, first, to reduce the rate of use of our coal to a minimum, and second, to study how motive power is to be procured and industry carried on in a coal-less Britain.

In evidence given before the Royal Commission, Dr. G. T. Beilby, F.R.S., makes the interesting calculation that out of an annual consumption of from 143 to 168 million tons of coal, there is a possible saving of from 40 to 60 million tons. I have taken Dr. Beilby's figures for the higher consumptions mentioned, and calculated from his division the percentage used for each separate purpose in the Table on page 598.

Dr. Beilby's estimated saving is thus 60 out of 168 million tons annually, 35·7 per cent. of the portion used for home consumption, or 26·1 per cent. of the total, including the exported coal, and it increases the coal life of our country to 676 years. Dr. Beilby pointed out in a note published eight years later by the British Science Guild, that the large gas-engine had not developed so rapidly, and the steam-turbine had advanced more rapidly than expected, so that the savings he anticipated had not yet been

—	Consumption in Millions of Tons.	Percentage.	Possible Saving.	How Saved.
Railways	14	8·4	7	Electric Traction.
Steamers	8	4·7	—	—
Factories	45	26·8	30	Gas Generators and Engines.
Mines	12	7·2	7	Gas-Engines and Recovery Ovens.
Blast-Furnaces	18	10·7	3	
Iron and Steel	12	7·1	3	Gas Generators and Coke.
Other Metals	2	1·2	—	—
Brickworks, Potteries, Glass and Chemical Works	6	3·6	2	Gas Generators.
Gas Works	15	8·9	—	—
Domestic Purposes	36	21·4	8	Gas Cooking, Heating, Briquettes and Coke.
	168	100·0	60	

realized. Even without the superior thermal efficiency of the internal-combustion engine, large steam-turbines generating power at central stations are capable of reducing the 45 million tons of coal required for power in factories to nearly Dr. Beilby's figure.

Under pressure of necessity, however, it will prove possible to make other economies, which, however, involve greater changes. Thus, exhaust heat from steam- and gas-engines is utilized at present to a certain extent in heating buildings and carrying on various manufacturing processes, but no comprehensive attempt has been made to supply motive power, light and heat from the combustion of the same fuel. Large central stations with gas-generators and high efficiency gas-engines would give all the motive power required for factories on 15 million instead of 45 million tons of coal, as shown in the Table; but even then the waste heat from water-jacket, exhaust gases, and gas-producers, equals that produced by burning 10 million tons. This distributed through a city as steam at 30 lb. or so pressure above atmosphere could readily supply heat for the household to warm the rooms and perform cooking operations The high efficiency of steam-heating and cooking

would enable the heat of 10 million tons to do the domestic work at present performed by 36 millions. The open fire would be missed, with its pleasing radiation, but under pressure of circumstances we should be forced to dispense with it. But even if we allow 12 million tons of the 36 to be still used for radiation, the total coal bill would be reduced to one-half, and the industrial life of the country increased to 1,000 years. From this it appears that our present fuel-needs might be met by the use of half our coal consumption. Further economy may be effected by the extended adoption of water-power.

In order to reason with any approach to accuracy, it is necessary to arrive at some probable estimate of the total power available in the world, and to extend the inquiry not only to a coal-less England, but to a coal-less and oil-less world. The total energy available to us is due to solar radiation, past and present, tidal energy, and the earth's internal heat. The great source of all our energy is, of course, solar radiation. Taking Sir J. J. Thomson's estimate of 7,000 h.p.* per acre as the total radiation of the sun absorbed on the earth's surface with a clear sky, this is sufficient to produce 4,480 h.p. per square mile, assuming an absolute efficiency of conversion of one-tenth per cent. Such a result, however, can only be hoped for in desert districts, where the sun's rays are not obstructed by clouds or vapour. If this enormous energy were easily available, then engineering problems would chiefly deal with the generation of motive power in great deserts such as those existing in Africa, and the transmission of the power so generated to districts where man could live and pursue his manufactures.

Sun Power.—Though many engineers, including Ericsson, have experimented with sun engines,† so far no method of using the direct solar energy of radiation has been invented which is capable of

* Professor A. H. Gibson gives the value as 8,000 ft.-lb. per minute per square foot in areas between the Equator and 45° North and South Latitudes.

† Professor Gibson gives an account of recent solar motor experiments.

supplying any large amount of power. The world, however, may be considered as a huge solar engine, in which the waters of the seas are evaporated by the heat absorbed, and much of the vapour carried to high levels, at which it is deposited as water, and flows down to the sea. By this process we get a complete cycle of operations, including evaporation of water into steam, condensation of the steam into water, evaporation again, and so on. In falling from the high level to the low level of the sea, power can be obtained from this water. Hydraulic power, in fact, is a form of sun power, and will continue in existence long after all the coal and oil in the world has been exhausted. Coal and oil have also been produced by the action of the great solar engine, and they contain a portion of the energy of radiation of past ages, stored up in the growing wood and leaves of plants; accumulations which are now being rapidly drawn upon by mankind. Coal and oil are thus the result of past radiant energy, while wind and water-power are due to present radiant energy. In one case the store in the earth is being used up and cannot be replaced; in the other case, so long as the solar system lasts, power exists also. Mr. Ellington very clearly took this view in the first Hawksley Lecture, when he said: "On a review of the whole subject, it appears that water-power is likely to become increasingly important. It is perennial in its source. As a mechanical agent it has numerous ramifications, which are constantly extending, and its direct application to industry offers a large field for the exercise of the talents of the inventor and the engineer."

Increasing Importance of Hydraulic Power.—Although I have devoted myself to the rival power obtained by internal combustion, I thoroughly agree with what Mr. Ellington has said. Undoubtedly as time goes on, hydraulic power must become of increasing importance. Mr. Ellington estimated the average rainfall in the United Kingdom as 25 inches per annum, and he calculated that, assuming a fall of 500 feet, this gave 100 h.p. per square mile continuing throughout the year. But a small part of the area of the United Kingdom is at so high a level as 500 feet. The total

area of the United Kingdom is roughly 121,000 square miles. Taking suitable ground of 500 feet level at 5 per cent. of the total area, and assuming it possible to construct artificial lakes by means of dams, from this area nearly two million h.p. could be obtained, available for eight hours per day every day of the year. In some areas of England the rainfall is more than 60 inches per annum, and on these areas the altitude is about 1,000 feet.

Mr. Alexander Newlands, Chief Engineer of the Highland Railway, read a most interesting Paper before the British Association in 1912, on Scottish Water-Power, in which he adopts the view of Professor G. Forbes, F.R.S., that the available hydraulic power in Scotland exceeds one million h.p. Mr. Newlands has investigated many convenient power stations, and gives a list of forty-five localities, from which he considers a total of 205,000 h.p. could be obtained. He states that the Kinlochleven Works of the British Aluminium Co. on the west of Argyllshire cost £600,000, and develop 30,000 h.p., at a capital expenditure of £20 per h.p. The total cost of current used is one-sixteenth of a penny per unit, after allowing for interest on capital and depreciation.

The average investment cost of all American water-powers he gives as £40 per h.p. developed. Mr. Newlands comes to the conclusion that installations costing up to £20 per h.p. could deliver power at a cost with which no steam plant could hope to compete. In Norway and Sweden, where Pelton wheels are used, with high heads, installations exist which cost £10 per h.p., and in these countries power has been advertised for sale as low as thirty shillings per h.p. per annum. Mr. Newlands quotes the *Electrical Review's* comparison of the minimum costs of an electrical horse-power per annum from

	£	s.	d.
Water in Switzerland	1	19	0
Steam in England	4	11	8
Blast-Furnace Gas in Germany	4	1	7
Producer-Gas in England	5	0	0

From these figures it is evident that in Scotland, even at the present time, hydraulic power presents economic advantages when

compared with power obtained from the cheap coal of to-day by steam- and gas-engines. With increasing scarcity of coal, undoubtedly hydraulic power will in the future show greater advantages, and even in England and Ireland it might be possible to earn interest on capital expenditure greater than £40 per h.p. By great engineering works, it might be just possible to obtain perhaps three million h.p. from areas which could be given up for the purpose. This power obviously is insufficient for British needs.

To increase production, other sources may be drawn upon. In the conditions assumed, the only other source of energy at all comparable to water is the yearly fuel growth of trees and undergrowth. It is difficult to arrive at any probable value of wood growth in the United Kingdom. The whole area under forests is 3,081,754 acres, and I can find no published figures dealing with annual yield. The total area of German forests is given as 34,569,800 acres, and the yearly yield as 26,183,410 cubic yards of timber, and 23,348,640 cubic yards of fire-wood. Taking a cubic yard of fire-wood as weighing 0·6 ton gives 14 million tons as the annual growth of fire-wood in Germany. This equals 6,200,000 tons of coal in heating value. The forest area of the United Kingdom is about one-eleventh of that of Germany, so that on this scale we could only produce heat equal to 563,000 tons of coal. Obviously fire-wood growth with us cannot be expected to give more than about 350,000 h.p. No doubt larger areas will be devoted to forests in the future, and greater power obtained, but I fear even then the yield could not make up for the loss of coal. There only remains wind and tidal power for consideration. Wind power may be neglected. Tidal power, however, would add materially to the total, but at the cost of great, inconvenient, and expensive works.

Oil does not materially affect our problem. The total oil produced from wells and distilled from shale in the world is about 5 per cent. of the weight of coal raised, and according to Sir Boverton Redwood, even if the whole of the crude petroleum were employed as fuel, in steam raising, it would not replace, allowing for its high thermal value, much more than 5 per cent. of the world's output of coal; while if used in internal-combustion engines,

it would be equivalent as a source of power to about 15 per cent. of coal. Only a small proportion, however, of the crude petroleum can be regarded as available for use as a source of power, for by far the larger part is in demand as an illuminating agent, and as a lubricant for machinery.

Sir Boverton Redwood states also: "Some of the older oil-fields of the United States are becoming exhausted, and Dr. David T. Day, of the United States Geological Survey, considers that at the present rate of increase of the output of petroleum, the known oil-fields of that country will, on the basis of the minimum quantity of oil obtainable, be exhausted by the year 1935, whilst even if the present output were only maintained, the supply would, on the same basis, not last for more than 90 years." The oil supply of the world, accordingly, does not greatly help us to extend the duration of industrial civilization. The earth's heat—the only other source of power—is unavailable, and could not be drawn upon in our present state of knowledge. In the absence of coal, then, it appears that all the energy available for power in the United Kingdom would not exceed 4 million h.p., or 6·5 million h.p. less than is at present used in our factories alone.

But we also require fuel to produce power for railways and ships. In the Table (page 598) railways use 8·4 per cent. and factories 26·8 per cent. of our total coal consumption. Assume that locomotives require the same weights of coal as factories for each horse-power developed, then the locomotive power of our country is about 3·3 million h.p. Our mercantile marine requires another 5 million h.p., and the Royal Navy in time of war also requires 5 million.

Altogether, to carry on the industrial civilization of these islands in time of peace, on the scale of to-day, absorbs a power of about 19 million h.p., and without coal we could only obtain 4 million. Obviously, a change of condition such as this necessarily involves great modifications in our social life and a large reduction in the population which we can support in comfort.

Taking 1,100 million tons as the world's output of coal for 1907, on the assumption that the proportion used for factories and railways is the same as in our country, then the world's factories

require 295 million tons, and railways 93 million tons. Assuming the same consumption per h.p., the world's factories require 60 million h.p., and the world's railways 19 million. I have estimated the power of the world's shipping as—mercantile marine, 10 million h.p.; warships, 13 million h.p. The total power used in the world generated by the combustion of coal is thus of the order of 100 million h.p.* :—

	Million h.p.
World's Factories	60
World's Railways	19
World's Ships	23
	102

This estimate does not include existing hydraulic power. Assume it to be 13 million h.p. Then the total power required in a coal-less world would be 115 million h.p. There is little doubt that the hydraulic supply of the world † is capable of producing more than this, so that even when our world's coal is exhausted all the power required will be forthcoming. In this case, however, storage batteries must be greatly improved to enable ships to be propelled electrically. But as about 40 per cent. of the world's coal is consumed in producing motive power, 60 per cent. of the heat value of the total coal must be replaced from some other source. The only further source of heat would then be growing wood; a large quantity would be grown in tropical countries and transported as charcoal, but fuel so obtained would be expensive, and heat and chemical action in domestic and metallurgic use would be economized to the utmost.

It is very evident, therefore, from this short discussion, that the line of the engineer's duty is to be found in economizing all the energy remaining in these islands in the form of coal, and thus postponing the period of industrial change in England. Engineers have long felt the pressure of this duty, and have strenuously

* Professor Gibson gives the same figure, 100 million h.p., but arrives at it in a different way.

† Professor Gibson's estimates of the total available water-power of the world is 200 million h.p.; United States of America water-power from 35 to 55 million h.p., of which 5·3 million were utilized in 1908.

endeavoured to find means of obtaining power at less and less fuel cost; so that even while Watt and Boulton were still struggling to make the condensing steam-engine a commercial success, others were experimenting with various schemes which did not require the use of steam. In these days it was felt that part of the loss of energy experienced in obtaining motive power by steam was due to the latent heat of the steam in passing from the liquid to the gaseous state. This was true in a limited sense, but the science of thermodynamics had no existence until about 1840, and accordingly engineers had nothing to guide them in determining the laws by which heat produces mechanical work. The idea, however, that latent heat absorbed heat energy undoubtedly had its effect in provoking attempts to use atmospheric air as a source of motive power.

Stirling and Ericsson's Hot-Air Engines.—The earliest hot-air engine which was reasonably successful was the invention of a clergyman, Dr. Stirling. In this engine air was heated at constant volume with increase in pressure, and the power was obtained by subsequent expansion. In another engine of what is now known as the constant-pressure type, Ericsson, the well-known American engineer, compressed air, heated it at constant pressure, and expanded it in a larger cylinder than the compression cylinder. In both the Stirling and the Ericsson engines a contrivance known as the regenerator was used, which was the subject of much controversy and misunderstanding. The early Stirling engine was produced in 1815, but thirty years after a Paper was read by Mr. James Stirling at the Institution of Civil Engineers upon "Stirling's Improved Air Engine." The main improvement consisted in working with air at a greater original density than that of the atmosphere, and the engine had so far succeeded that two had been used at the Dundee Foundry Co.'s works, one giving 21 and the other 45 h.p. Mr. Stirling claimed that the 21 h.p. engine required only $2\frac{1}{2}$ lb. of coal per h.p. hour. This is an extraordinarily good result, and could only have been obtained by the action of the regenerator. It is clear, however, from the Paper and from the discussion, that many engineers then imagined that,

with a perfect regenerator, no heat would disappear in performing work. The speakers in this discussion included Robert Stephenson, and, curiously enough, he plainly misunderstood the whole process of action of Stirling's engine. His remark on the regenerator was illuminating: "He understood the process to consist of heating the air in a vessel, whence it ascended to the cylinder between numerous thin laminæ, by which the caloric was absorbed, to be again given out to the descending air. Now, it appeared to him that, though the ascending process was natural and easy, the reverse action would require a certain expenditure of power, in the depression of the plunger." A Mr. Cottom said: "It was evident that if it was practicable to arrive at the theoretical condition of the absorption of all the caloric by the thin laminæ during the upward passage of the air and the giving it out again during the downward passage, there would not be any loss of heat."

Other Papers were read on the same subject at the Institution of Civil Engineers in 1853, and the discussion interests us particularly, because Mr. Thomas Hawksley joined in it. Mr. Hawksley considered that the machine involved a mechanical fallacy, and that the regenerator produced no mechanical effect whatever. Here Hawksley was clearly in error, but he erred in good company, because at the same time the famous Dr. Faraday said: "Twenty years ago he had directed his attention to this question, and from theoretical views he had been induced to hope for the successful employment of heated air as a motive power; but even then he saw enough to discourage his sanguine expectation, and he had, with some diffidence, ventured to express his conviction of the almost unconquerable practical difficulties surrounding the case, and of the fallacy of the presumed advantages of the regenerator." Brunel also considered the use of the regenerator to be an entire fallacy. Sir George Cayley, about the same time, described another hot-air engine, which may be considered as the first of the internal-combustion type acting with solid fuel under constant pressure. In his engine he pumped air into a furnace, and led the heated products of combustion through valves into the interior of a cylinder. He also was unsuccessful.

The Stirling and Ericsson engine worked, but both engines were extremely bulky and heavy. Ericsson built a hot-air engine for operating the hot-air ship " Ericsson " in America, and the cylinders were no less than 14 feet in diameter. From these he got only about 300 h.p. Both types of engine failed, because of the rapid burning out of the cylinder bottoms with the direct action of the fire, as it was found impossible to heat the air rapidly enough to the required temperature without maintaining the temperature of the metal surfaces much higher than the maximum temperature to be attained by the air. Some inventors, as has been stated, proposed to heat the air by combustion, and Cayley's was the first attempt to do this with solid fuel. Cayley, however, introduced difficulties as grave as external heating, hot gases had to pass through pipes and valves to the motor cylinder, and this made it impossible to maintain a high temperature without damage to the machine.

Inventors dealing with internal combustion introduced into a cool cylinder a mixture of gas or inflammable vapour and air at atmospheric pressure, ignited this mixture at constant volume, and drove a piston by the increase in pressure. Professor Farish of Cambridge, at his philosophical lectures at the University, exhibited a model engine so operated as early as 1817. Other inventors attempted to operate their engines by atmospheric pressure, producing the necessary vacuum or reduction of pressure by the combustion of an inflammable gas in air.

The Cecil Engine.—The Rev. W. Cecil, M.A., of Cambridge, read a Paper in the year 1820 before the Cambridge Philosophical Society, on the application of hydrogen gas to produce a moving power in machinery, with a description of an engine which is moved by the pressure of the atmosphere upon a vacuum caused by explosions of hydrogen gas and atmospheric air. He described an engine which he had constructed to operate on the explosion vacuum method. He thus explains the principle of his engine: " The general principle of this engine is founded upon the property which hydrogen gas mixed with atmospheric air possesses of exploding upon ignition so as to produce a large imperfect vacuum.

If two and a half measures by bulk of atmospheric air be mixed with one measure of hydrogen and a flame be applied, the mixed gas will expand into a space rather greater than three times its original bulk. The products of explosion are, a globule of water formed by the union of the hydrogen and the oxygen and the atmospheric air and a quantity of azote, which, in its natural state (or density, 1) constituted 0·556 of the bulk of the mixed gas. The same quantity of azote is now expanded into a space somewhat greater than three times the original bulk of the mixed gas—that is, into about six times the space which it occupied before; its density is therefore about one-sixth, that of the atmosphere being unity. If the external air be prevented by a proper apparatus from returning into this imperfect vacuum, the pressure of the atmosphere may be employed as a moving force nearly in the same manner as in the common steam-engine; the difference consists chiefly in the manner of forming the vacuum."

Fig. 1, Plate 7, shows in perspective the drawing accompanying Mr. Cecil's Paper in 1820. The operation of the engine consisted in drawing into the cylinder a proportion of atmospheric air and hydrogen, igniting this mixture at the end of the stroke, allowing the hot gases to be discharged from the cylinder by the pressure of combustion, then cooling the gases in the cylinder and producing a vacuum to operate the piston.

The Figure also shows different views of the engine, and a diagram showing the power obtained by the vacuum. Mr. Cecil stated that the engine rotated at 60 revolutions per minute; in practice it was found to work at considerable power and perfect regularity. In the model constructed, the engine used 17·6 cubic feet of hydrogen gas per hour. Evidently, however, the engine was rather noisy, because the inventor stated: "To remedy the noise which was occasioned by the explosion, the lower end of the cylinder A, B, C, D, may be buried in a well, or it may be enclosed in a large air-tight vessel." This engine is very crude, but extremely ingenious. It is also interesting to note that Cecil made experiments by which he determined approximately the maximum pressure produced by means of a mixture of hydrogen and

atmospheric air. He gives this maximum pressure as 180 lb. per square inch absolute.

The Brown Engine.—Mr. Cecil did not carry his invention further, but another inventor, Mr. Samuel Brown, took out patents in 1823 and 1826 in which he operated by filling a vessel with flame to expel its contained air and throwing in a jet of water to condense the flame. This produced a partial vacuum, and the atmospheric pressure was made available for utilizing the power by means of an ordinary piston. Samuel Brown was very persevering, and according to the *Mechanics' Magazine* published in London in August 1824, he had then made a model which raised 300 gallons of water 15 feet high on one cubic foot of gas. In 1832 it appears that four of his engines were in use for pumping:—(1) One at Croydon at the canal, raising water from a lower to a higher level; (2) one at Soham in Cambridgeshire, for draining part of the middle fen district; (3) one at Eagle Lodge, Old Brompton; and (4) one at Eagle Lodge, Old Brompton, of the beam type. It was stated that the cylinder of the Croydon engine was 3 feet 6 inches in diameter by 22 feet high. Engine No. 3 was inspected by the editor of the *Mechanics' Magazine.* Its cylinder was 3 feet $8\frac{3}{4}$ inches diameter by 22 feet high; and it discharged 750 gallons per stroke, four strokes per minute, 12 feet high. Brown claimed in a circular published in 1832 that the coke and tar obtained in making coal gas for the Croydon engine were sold for such sums as produced a profit in addition to giving motive power for nothing. He stated that the whole annual expense of the Croydon gas vacuum engine, including coal, wages, repairs, depreciation, rent, amounted to £666 14*s.* 0*d.*, while the receipts from the sale of coke and tar were £769 12*s.* 0*d.*, so that the annual profit was £102 18*s.* 0*d.*, without counting the value of the pumping work done, which previously cost the Canal Co. £275 per annum to effect by steam-engine. This state of affairs, however, could not have been permanent, as after some years of work the engines were displaced. Brown also applied his vacuum gas-engine to driving a carriage in 1825 and to propelling a boat on the

Thames in 1827. These early attempts were obviously inspired by the low-pressure steam-engine with its vacuum obtained by steam, but no real success was attained, the gas consumption—that is, the consumption of heat for producing a given power—being very high.

Lenoir Gas-Engine.—Meanwhile the work of Joule, determining the mechanical equivalent of heat, taken together with that of Macquorn Rankine, Thomson and Clausius, based partly on the earlier investigations of Carnot, had developed a definite theory of the relationship between heat and mechanical work. Accordingly, we find the advocates of internal combustion increasingly active, and in 1860 Messrs. Marinoni introduced in Paris the famous Lenoir gas-engine. In it the principle is exceedingly simple and evident. The piston moved forward a part of its stroke by the energy stored in the fly-wheel, and took into the cylinder a charge of gas and air at the ordinary atmospheric pressure. The valves cut off communication, and the explosion was occasioned by electric spark. The piston was thus propelled to the end of the stroke. Exhausting was performed exactly as in the steam-engine. This engine was practicable but very uneconomical. It was largely used, however, for pumping. One such engine was inspected by the Author at Petworth House, Petworth, in 1882, and it had then been working, pumping water, for about twenty years. This engine was replaced some years ago by an engine of the National Gas Engine Co.'s manufacture, which was used both for pumping and electric lighting. Fig. 2, Plate 8, is from a photograph showing a Lenoir engine of ½ h.p. built by the Reading Iron Works, Ltd., about 1866.

The Engines of Otto and Clerk.—It was very soon found that, to obtain economy in an internal-combustion engine, compression was necessary, and the history of the modern internal-combustion engine dates from Beau de Rochas' famous pamphlet in 1860, in which the alternate use of a cylinder as pump and motor and the use of considerable compression was fully described. To the late Dr. Otto, however, belongs the honour of bringing this type of engine into practical use. This he did in 1876. Otto's was the first compression gas-engine to succeed in practice. I produced my

first compression engine in 1878, and exhibited it at work at the Kilburn Royal Agricultural Show in 1879. In this engine compression was also used, but an impulse was obtained at every forward stroke of the motor piston. The engine best known, however, as of the Clerk type was not produced till 1881, in which year it was exhibited at an Electrical Exhibition in London and later in Paris. This engine was the first in which the piston overran ports by which the exhaust was discharged, and where the charge was admitted to the cylinder from a separate pump in such a way as to discharge the exhaust products before it. Practically all the internal-combustion engines of the world now operate either on the Otto four-stroke or on the Clerk two-stroke system. In these engines the explosion takes place at constant volume, so that the pressure rises.

Constant-Pressure Engine.—As far back as 1873 a constant-pressure engine was introduced by an American inventor, Brayton. This engine resembled a hot-air engine in which air was compressed into a reservoir at a constant pressure, then expanded into a working cylinder at the same pressure, and the volume increased by the formation of flame. An American engine of this type is shown in Fig. 3, Plate 8. Brayton's engine used light petroleum, and it had a certain success. It had considerable application for stationary work, and it was intended to apply also to the propulsion of boats and vehicles. The modern constant-pressure engine, however, does not work in the Brayton manner. The Diesel type depends upon the compression of air to about one-twelfth of its original bulk in a cylinder, the raising of the temperature of the air to a sufficient extent to ignite heavy oil when injected into it in fine spray. The injection occurs from the beginning of the stroke during a very small advance of the piston on its forward stroke. A diagram is thus produced which is substantially a constant-pressure diagram. This engine is extensively used for many purposes, including pumping. It sometimes operates on the Otto and sometimes on the Clerk cycle. The smaller engines use the Otto method and the larger the Clerk method.

Comparison of Steam and Internal-Combustion Engines.—During many years, compression was continuously increased in constant-volume types of engine, and with increased compression came increased economy of fuel. At the same time coal-gas was supplemented by other gaseous fuels; first, Dowson pressure-gas made from anthracite, then suction-gas from anthracite, coke and other fuels, and later waste gases from the blast-furnace. Many substances also were utilized to produce gas for engines, many of them waste products, sawdust, dried peat and wood chips of different kinds. Bituminous fuel was also used, at first only in conjunction with ammonia-recovery processes; later, on a smaller scale, for gas only.

Many obstacles were found to increasing engine dimensions indefinitely. In the early days of the internal-combustion engine, enthusiastic pioneers like myself considered that ultimately the internal-combustion engine would entirely displace steam. In a Paper read at the Institution of Civil Engineers in 1882, I stated: "The gas-engine is as yet in its infancy, and many long years of work are necessary before it can rank with the steam-engine in capacity for all manner of uses; but it can quite well be made as manageable as the steam-engine in by no means a remote future. The time will come when factories, railways, and ships will be driven by gas-engines as efficient as any steam-engine, and much more safe and economical of fuel. Gas-generators will replace steam-boilers, and power will not be stored up in enormous reservoirs but generated by coal direct as required by the engine.

"The steam-engine converts so small an amount of the heat used by it into work that, although it was the glory and honour of the first half of the century, it should be a standing reproach to engineers and scientists at the present time having constantly before them the researches of Mayer and Joule."

Other engineers like Sir Frederick Bramwell shared in this feeling. Sir Frederick even went so far as to predict that, by 1931, steam-engines would only be found in museums. A gallant attempt was made by those interested in the gas-engine to fulfil Sir Frederick's prophecy, and very great progress has been made.

The internal-combustion engine has acquired a definite position in the engineering world, and shares largely with the steam-engine in the power production of the world. Progress, however, has revealed conditions of unlooked-for advantage in the steam-engine which so far has not been attained in internal-combustion engines. The advent of the steam-turbine, developed by the genius and indefatigably hard work of the Hon. Sir Charles Parsons, has proved clearly that, for large powers, reciprocating pistons operating in cylinders must become a thing of the past.

In the early days of the compression internal-combustion engine (about 1880) the average efficiency of the steam-engines in use was very low. In Britain an average steam-engine of medium size would usually be found to convert only 5 per cent. of the total heat of the coal burned under the boiler into indicated work in the engine-cylinder. The best result obtained, even with large reciprocating steam-engines, about that time did not exceed 10 per cent., calculated in the same way. The early Otto cycle gas-engines of the same date converted 16 per cent. of the total heat of the coal-gas used into indicated power within the cylinder. As years went on this efficiency was greatly improved upon, and about 1910, internal-combustion engines of 15 inches diameter cylinder, when carefully made, could be relied upon to give an indicated thermal efficiency of 35 per cent., and in some experimental tests even so high as 40 per cent. has been obtained. At one time it was believed that as gas-engine cylinders increased in diameter, efficiencies would also increase, because of the diminished proportional surface causing less heat loss from the hot flame to the enclosing walls. It was found, however, that increase beyond 15-inch cylinder diameter produced but little practical change in actual indicated thermal efficiency. Careful investigation into the phenomena of the gas-engine cylinder by many investigators, including the present Author, proved conclusively that little gain could be expected from further increase of cylinder dimensions. Much scientific work had been done by the British Association Committee on Gaseous Explosions and by Committees of the Institution of Civil Engineers and of the Institution of Mechanical

Engineers. These investigations clearly proved that definite properties of the working fluid limited the thermal possible efficiencies, so that if even the whole heat-flow through the sides of the cylinder be put an end to, only a moderate increase in indicated thermal efficiency would result. Distinct limits to increased thermal efficiency were shown to exist. The conditions, however, of heat-flow within the cylinder were more and more clearly understood, and were found to be greatly affected by cylinder dimensions; increased cylinders prejudicially affected the power of the cylinder-jacket and piston to dissipate the heat of the explosion and so tended to undue rise in wall temperature. In other words, it was found that the larger the cylinder became, the greater became the difficulty of preventing heat fractures in breech-ends, cylinders, liners, and pistons. It was speedily found that in the ordinary four-stroke or Otto cycle-engine, 22 inches to 24 inches was the safe limit of cylinder diameter for engines having unwatered pistons. Immediately these dimensions were exceeded, it became necessary to pump water through a hollow piston and also through the exhaust-valve, in order to keep down wall temperature and avoid fracture and pre-ignitions. Although watering a piston does not appear to be a formidable operation, yet it inevitably increases the weight of the piston and reciprocating parts of an engine, and so diminishes the possible piston-speed by increasing the stresses due to the acceleration and retardation. Engines as large as 51-inch diameter cylinder have been made, but the weight required per horse-power was very greatly increased. The law of similar structures shows clearly that for entirely similar engines of increasing cylinder dimensions, the weight per indicated horse-power increases directly with the cylinder diameter. This is true of steam- as well as of gas-engines, but the gas-engine is at a disadvantage because the ratio between maximum and mean available steam-pressure is much more favourable than that between maximum explosion and mean pressure; and, further, the double-acting steam-engine for a single piston produces two impulses per revolution, while a double-acting four-stroke engine requires two revolutions within which to produce two impulses. Accordingly,

the weight of a gas-engine for a given power is greater than that of a steam-engine of equal cylinder diameter. A gas-engine is thus necessarily heavier than a steam-engine of the same power and cylinder dimensions. The law applies even with greater force to engines of the Diesel type, where pressures of compression of 500 lb. per square inch must be provided for, and a sufficient margin must be left to allow for even 1,000 lb. per square inch, due to explosive instead of constant-pressure ignition, which sometimes occurs, especially when starting. All these difficulties tended to restrict the commercially saleable internal-combustion engine to moderate powers. On the Continent engine-builders favour large cylinder slow-running engines of great weight; but in England such engines never became really popular, and the great gas-engine trade of Britain has been built up on the basis of a cylinder not exceeding 24-inch diameter usually running with an unwatered piston and exhaust-valve. In England the multiple cylinder high-speed internal-combustion engine has had considerable success, and is now made by well-known engineering companies in sizes up to about 3,000 h.p. for one engine.

In reciprocating steam-engines for fast battleships and passenger steamers, the limit of weight for power was approached about 1895, and it became evident that, if higher speeds were required, some other method of obtaining motive power must be adopted. Sir Charles Parsons began his work on the land steam-turbine in 1884, and began experiments on the marine steam-turbine in 1894, and in a marvellously short time he passed from the engines of the "Turbinia," giving 2,000 shaft h.p., to the engines of the "Mauretania," giving 70,000 shaft h.p. It was speedily proved that the steam-turbine in various forms gave large powers within limitations of weight impossible by any other method. Powers of 100,000 h.p., for example, now frequently found in battle cruisers, such as the "Lion" and "Tiger," could not have been obtained from reciprocating steam-engines at all; still less could such powers have been obtained from internal-combustion engines of any type, whether gas or Diesel oil. Further improvements in gearing the steam-turbine to its propeller enabled the weight of the turbine to

be greatly reduced, and its speed of rotation arranged for maximum efficiency, while allowing the speed of rotation of the propeller also to be arranged for maximum efficiency. Consequently the turbine became more and more economical.

In the early days of the small steam-turbine the steam consumption was large, but now Sir Charles Parsons is able to offer a large power turbine with a steam consumption as low as 9 lb. per shaft horse-power. In such an engine 20 per cent. of all the heat of the steam is converted into shaft horse-power, and with a boiler of ordinary efficiency this may be taken as giving a return of at least 15 per cent. of the whole heat of the fuel in useful work transmitted by the shaft. It was speedily found that these large turbine engines gave but little trouble in the engine-room compared with their reciprocating predecessors, and as a result the Parsons steam-turbine has become in a few years supreme in all battle fleets; indeed, if the total horse-power upon the seas of the world be taken as about 24,000,000 h.p., 8,000,000 h.p. is accounted for by the Parsons turbine.

The difficulties found to accompany increasing cylinder dimensions have thus limited the internal-combustion engine to comparatively small units; a 5,000-h.p. engine is considered very large for any form of gas-engine; a 5,000-h.p. steam-turbine forms an ordinary unit for an electric light station engine. Obviously the internal-combustion engine must be considerably modified before it can equal the steam-turbine as a mechanism for producing large powers. As a machine for converting heat into work, the internal-combustion engine is still supreme; but engineers must now devote themselves to overcoming the mechanical difficulties of very large powers. It is possible to increase the thermal efficiency still further, but gain in that direction will not help us in our competition with the steam-turbine. So far as I can see there is no hope of an indefinite increase in power using reciprocating pistons. Something must be done to introduce the rotary principle. Many attempts have been made to produce a gas-turbine, the most important recent attempt being that of Mr. Holzwarth, whose gas-turbine has been built by Messrs. Brown,

Boveri and Co.; but, so far as I know, no success has yet been attained. The theory of the Holzwarth turbine in its form last known to me necessarily gives a somewhat low thermal efficiency; I have calculated it to be 15 per cent. of the heat of the working fluid, and in 1912 the extreme value claimed by Mr. Holzwarth was 23 per cent. Such results do not practically improve upon those of the largest steam-turbines.

Other methods, however, of dispensing with the reciprocating piston and cylinder are quite practicable. The large Humphrey pump described in the second Thomas Hawksley Lecture dispenses with pistons, and utilizes an explosion-chamber in which gases are compressed and ignited, and operate by throwing a heavy column of water into motion. This method has advantages, but it is necessarily heavy for a given power. It appears possible to use water in another manner by filling a chamber, exploding a compressed mixture above the water, and forcing the water through a jet to operate a turbine of the Pelton type. Arrangements would be made to allow for the varying velocity of the water due to fall of pressure by expansion, and it would be quite possible to obtain an efficiency between explosion-chamber and Pelton wheel of about 80 per cent. Such a turbine could be made to work using the same water repeatedly, and high efficiency combined with light weight is possible. A brake efficiency of 30 per cent. is possible. Experiments in this direction are worthy of consideration. Before such engines could compete for the highest powers reached by the steam-turbine, gas-producers must be considerably modified and improved. The Mond type producer using bituminous fuel has been fairly successful, but it depends largely for success on the recovery of ammonia, and this involves a bulky and heavy plant. This is allowable in stationary installations, but for marine purposes much lighter and smaller producers would require to be designed capable of consuming bituminous fuel as completely as is done in a steam-boiler furnace, so that but little tar ever exists in the gas. If tar once gets into gas, an enormous scrubbing plant becomes necessary. Producers will require to be designed and experimented with, which avoid the huge scrubbing plant required at present in

all bituminous producers. With such producers and such engines a brake efficiency of 25 per cent. between fuel and Pelton wheel would not be difficult to obtain, and a 30 per cent. efficiency is quite possible.

With such mechanisms built in large power units, the power of Britain could be obtained for nearly one-third the present fuel consumption, and the work of the gas-engineer would thus materially aid in prolonging the coal life of Britain.

Progress of Indicated Thermal Efficiency.—So far the work of the engineer during the nineteenth and twentieth centuries has resulted in improving the indicated thermal efficiency from 3·8 per cent. obtained by the Boulton and Watt condensing low-pressure steam-engine to 35 and 40 per cent. obtained by explosion and constant pressure internal-combustion engines. The following Table shows the progress very clearly:—

Indicated Thermal Efficiency of Steam and Internal-Combustion Engine.

Steam.	*Indicated Efficiency.* Per cent.
Boulton and Watt Condensing Low-Pressure, about 1820	3·8
Cornish Engine, about 1850	9·0
Triple Expansion, about 1910	17·0
Parsons Turbine, about 1914	23·0
Internal-Combustion.	
Lenoir, about 1860	4·0
Compression—Constant Volume, (two or four stroke) 1876	16·0
Compression—Constant Volume, (two or four stroke) 1905	35·0
Compression—Constant Pressure (Diesel), 1910	40·0

The indicated efficiency refers to the proportion of the total heat of the steam or working fluid given to the engine converted into indicated work. The indicated work obtained for 100 heat units in the fuel is, of course, less because of boiler and steam-pipe losses; and, where a gas-producer is used, because of gas-producer losses. Assuming a very favourable figure for the efficiency between the

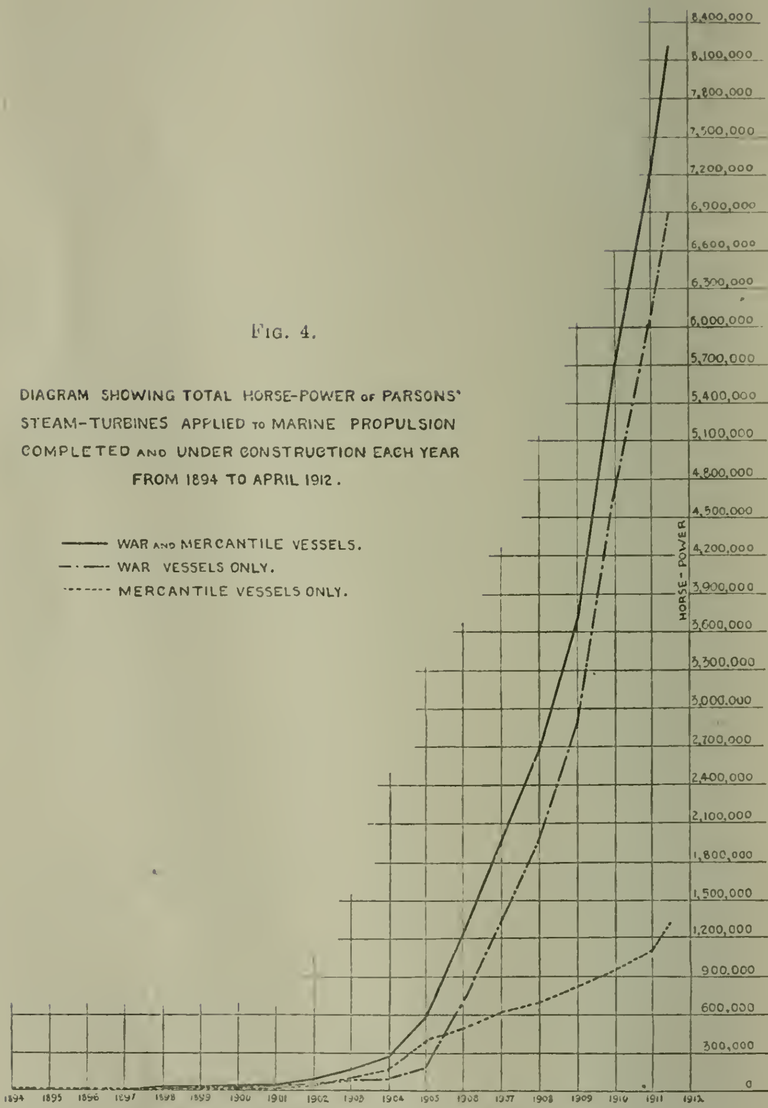
boiler and the steam-cylinder, 0·8, it will be seen that the indicated efficiency from the heat in the fuel in the case of the Boulton and Watt engine is only 3 per cent., and in the case of the explosion internal-combustion engine 28 per cent. Applying the same correction to the Parsons turbine, we get $18\frac{1}{2}$ per cent. as the best result of heat conversion from fuel to the shaft horse-power of the engine. In comparing modern efficiencies, therefore, the steam-turbine shows $18\frac{1}{2}$ per cent. heat conversion from the fuel against 28 per cent. heat conversion from fuel by gas-producer in the explosion gas-engines. From this it would appear that, even against the best steam-turbine, a very substantial advantage would be gained if internal-combustion engines were made of similarly high efficiency operating on the continuous rotating principle. This, however, is a matter for future development, and offers an excellent field for the young and ambitious engineer. At present the power in use by steam-turbine, both on sea and on land, is greatly in excess of that produced by stationary internal-combustion engines.

I am indebted to Sir Charles Parsons for two interesting curves shown in Figs. 4 and 5. Fig. 4 (page 620) gives the total horse-power of Parsons' steam-turbine applied to marine propulsion between the years 1894 and 1912. From this it appears that in 1912 over 8 million shaft horse-power of marine steam-turbines were either completed or under construction up to that date, while, as shown in Fig. 5 (page 621), to the end of 1911, $6\frac{3}{4}$ million horse-power had been completed for land purposes only. The power of stationary and marine internal-combustion engines of all kinds does not approach those figures. Still, the internal-combustion engine has made great progress, and undoubtedly the difficulties at present existing will be ultimately overcome. I fear, however, the solution of these difficulties will not enable Sir Frederick Bramwell's prediction to be accomplished even in 1931. Steam-engines, internal-combustion engines, and water-turbines and engines will even then exist together, each satisfying a separate want.

From what I have already said, it will be seen that engineers' efforts have been continuously directed for about 150 years

Fig. 4.

DIAGRAM SHOWING TOTAL HORSE-POWER of PARSONS' STEAM-TURBINES APPLIED to MARINE PROPULSION COMPLETED and UNDER CONSTRUCTION EACH YEAR FROM 1894 TO APRIL 1912.

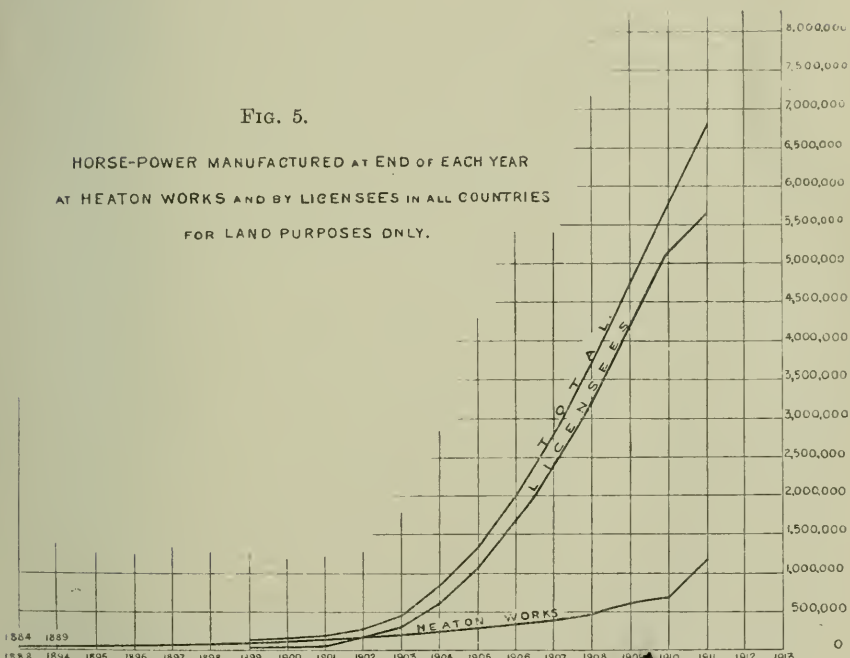


towards increasing the thermal efficiency of their prime movers; and in this quest for greater economy they have adopted a working fluid, flame, much more difficult to deal with than the early working fluid, steam.

When fuel becomes more and more expensive as our coal supply becomes obviously lessened, organized attempts will be made to obtain economies which are not worth while so long as

FIG. 5.

HORSE-POWER MANUFACTURED AT END OF EACH YEAR AT HEATON WORKS AND BY LICENSEES IN ALL COUNTRIES FOR LAND PURPOSES ONLY.



coal is cheap. Dr. Ferranti, in a Presidential Address to the Institution of Electrical Engineers, some time ago, dealt with the possibility of economizing for both power and heat by the electric conversion and conveyance of all the fuel energy. He showed the advantages of large central stations distributing electric current at a very low price—he mentioned one-eighth of a penny per unit—applying this current for all the purposes of heating, lighting and

motive power. So long as fuel is cheap, no doubt Dr. Ferranti's scheme might be usefully put into operation; but when fuel becomes really dear, too much heat is lost in the process of conversion into electric current. Central stations could be established in which steam-turbines were used for generating electric power, and where the exhaust-steam from the turbine was discharged at a pressure above that of the atmosphere, so as to maintain the temperature above 100° C. Such turbines would not give the thermal efficiency now obtained by Parsons, because they would lack the long expansion used by him in his largest and most efficient machines. The exhaust heat, however, could be used for manufacturing purposes and for household heating in a city, and a combined heating and thermal engine could thus be produced whose theoretical efficiency was 100 per cent.; the only loss would be that due to conduction during distribution, but heat supply for a city for heating houses and for doing low temperature manufacturing work could be readily obtained from the waste heat of the steam-turbines at the central stations. A large part of the heat necessary for comfortable life and industry could thus be obtained. Where medium high temperatures were required, a gas of low calorific value could be distributed, and efficient furnace arrangements could be made to obtain the necessary temperatures with a maximum economy. The waste heat from such furnaces could also be used to raise steam to enable general heat distribution to be conducted. Under these conditions many chemical processes, such as smelting, would be conducted electrically, with only such weight of carbon as was necessary for the chemical reaction—the high temperature for the reaction would be given by the electric heating. By combinations of steam-power and internal-combustion engines and exhaust heating, using both engine exhaust and furnace discharge, great economies would be effected and fuel consumption would be very greatly reduced. Dwelling-houses would be heated by circulating steam or hot water up to a certain temperature, and the added radiant heat necessary for comfort would be obtained either electrically or by burning small quantities of coal or gas in suitable fires. Although such conditions favour a low efficiency

use of steam for motive power, yet at a further scarcity price of fuel the high efficiency in the internal-combustion engine would find its field, because, broadly, a greater electrical heat and light could be obtained with a given fuel consumption, and the engine exhaust-gases would be at a higher temperature, and so have heat in a form available for a greater number of manufactures than the low temperature steam.

Future of Hydraulic Power.—Long before the final exhaustion of coal-pits, the increased expenditure necessary for heating and motive power would increase the pressure upon the hydraulic engineer, and undoubtedly much greater use would be made of water-power. I have already referred to Mr. Ellington's interesting calculation as to the total water-power of Britain determined by assuming all the rainfall to be available from a level of 500 feet above the sea, except that portion required for the use of the population, and absorbed by vegetation and evaporation. Mr. Ellington calculates on this basis that 35 million horse-power would be available for 2,000 hours in the year. If this could be done, of course, Britain, except for marine purposes, could be independent of coal. This calculation, however, requires two-thirds of the area of England to be arranged at the high level of 500 feet as a huge storage tank for rain-water, but with our present knowledge such an area is an engineering impossibility.

The future interaction of the world's three great prime movers —water, steam, and internal combustion—is very difficult to predict and appreciate. The effect, for example, of importation of coal from outside sources can hardly be predicted.

Whatever happens in the future, however, we may rest assured that hydraulic power will play a most important part, and that what has been called the "White Coal of the Mountains" will assume greater and greater importance with the increasing age of an industrialized world. In an able Paper read at the Zürich Meeting of this Institution in 1911, Mr. L. Zodel concludes with this statement: "Members of the Institution of Mechanical Engineers are indeed the representatives *par excellence* of steam

and steam power. Water power, the 'White Coal of the Mountains,' will hardly be of much importance in their own country, compared with that all-powerful 'Black Queen of Energy' of which they have an abundance; but it may, indeed, play a very great part in the development of the resources of the vast colonial possessions composing the British Empire." Undoubtedly Mr. Zodel saw clearly; but as time goes on Britain itself will become more and more dependent on hydraulic power.

Meantime, by the application of high-efficiency engines, the use of all waste heat for domestic and industrial purposes, and the application of all available water-power, all on a large scale, the engineer may extend the industrial period in England to over one thousand years. Long before that period our dominions across the sea will have become huge nations exceeding the 100 million souls as predicted by Professor Seeley, and even a coal-less England will remain great and prosperous, the intellectual and strategic centre of a vast empire.

Altogether the engineers of the future have before them vitally important and interesting problems, and on the success of their work depends the future of our country—whether we can support, five hundred years hence, an industrial population of fifty millions, or an agricultural one of about twenty millions. Of our immediate future I have no fear. We shall assuredly uphold our liberty and independence, notwithstanding all the warlike efforts of the Germanic powers; but our distant future undoubtedly depends more on the efforts of engineers than on the labours of war or politics.

The Lecture is illustrated by Plates 7 and 8 and 2 Figs. in the letterpress.

The attendance was 57 Members and 82 Visitors, including a few Ladies.

The Lecture was repeated by Dr. Clerk in Manchester, Glasgow, and Cardiff:—

At Manchester, at The Engineers' Club, Albert Square, on Tuesday, 2nd November. The President was in the Chair, and about 150 were present.

At Glasgow, at The Rankine Hall, Institution of Engineers and Shipbuilders in Scotland, Elmbank Crescent, on Monday, 8th November. Dr. Archibald Barr (*Member of Council*) presided, and 52 were present.

At Cardiff, at the South Wales Institute of Engineers, Park Place, on Thursday, 11th November. Principal E. H. Griffiths presided, and 59 were present.

The Institution of Mechanical Engineers.

PROCEEDINGS.

NOVEMBER 1915.

An ORDINARY GENERAL MEETING was held at The Institution of Civil Engineers, London, on Friday, 19th November 1915, at Eight o'clock p.m.; Dr. W. CAWTHORNE UNWIN, F.R.S., *President*, in the Chair.

The Minutes of the previous Meeting were read and confirmed.

The PRESIDENT announced that the following two Transferences had been made by the Council:—

Associate Members to Members.

ROBINSON, LESLIE HAMPTON, ...	London.
WALTHEW, JAMES GALLOWAY, ...	Manchester.

The PRESIDENT said the Council had considered the results of the October Examinations and found that twelve candidates had passed the Associate Membership Examination and twelve had passed the Graduateship Examination. Considering the times through which the country was passing, and the fact that the Examinations had hardly yet got established, he thought the Institution might be content that twenty-four candidates had passed the Examinations.

He now desired to refer to a subject of some importance. It had become difficult and dangerous to get home at night; the darkness and occasionally the interruption of traffic on the suburban lines had made it a matter of urgency to consider the proper time for holding the evening Meetings. At the last General Meeting of the Institution he took an informal vote, when there

(The President.)

was a majority in favour of the Meetings being held at six o'clock. The Royal Society of Arts were holding their Meetings at half-past four instead of eight o'clock in the evening; the Institution of Civil Engineers had decided to hold their Meetings at half-past five instead of eight o'clock; and the Council, after considering the subject in detail, and bearing in mind that some of the younger members appeared to think they would find it difficult to come as early as half-past five, had decided to hold the future Meetings of the Institution at six o'clock. He was afraid that during war time some difficulty might be experienced in maintaining the success of the Meetings, but he hoped the members would make an effort to support the Institution during the present exceptional period. It had been decided that tea should be provided at half-past five for any members who liked to come to it; the Meetings would be held at six, and they would be closed promptly at half-past seven. He hoped that would to some extent meet the difficulties of the time.

The following Papers were then read and jointly discussed :—

"The Chemical and Mechanical Relations of Iron, Molybdenum, and Carbon"; by Professor J. O. Arnold, D.Met., F.R.S., of the University of Sheffield, and Professor A. A. Read, D.Met., F.I.C., of the University of Wales, Cardiff; and

"The Cause and Effect of 'Ghost Lines' in large Steel Forgings"; by Professor J. O. Arnold, D.Met., F.R.S., of the University of Sheffield.

The Meeting terminated at Twenty Minutes past Nine o'clock. The attendance was 44 Members and 25 Visitors.

The Papers on "Carbides of Molybdenum" and "'Ghost Lines' in Steel Forgings" were further read and discussed at The Mappin Hall, St. George's Square, Sheffield, on Friday, 26th November 1915. Mr. J. Rossiter Hoyle, *Vice-President*, presided, and about 225 Members and Visitors were present.

THE CHEMICAL AND MECHANICAL RELATIONS OF IRON, MOLYBDENUM, AND CARBON.

By J. O. ARNOLD, D.Met., F.R.S.,
Professor of Metallurgy in the University of Sheffield,
and
A. A. READ, D.Met., F.I.C., of Cardiff,
Professor of Metallurgy in the University of Wales.

Summary of the Work of previous Investigators.—Thomas Blair, Sheffield, stated in 1894 that 1 per cent. of molybdenum rendered steel hopelessly red-short. Carnot and Goutal isolated from molybdenum steels, residues corresponding to the formulæ Fe_3Mo_2, and Fe_3C, Mo_2C (*Comptes Rendus*, 1898, vol. cxxv, page 221). M. Williams obtained Fe_3C, Mo_2C in the electric furnace (*Comptes Rendus*, 3rd October 1898).

J. A. Mathews states that molybdenum steels containing from about 1 to 3 per cent. molybdenum were red-short, but does not attribute this red-shortness to molybdenum (Journal, Iron and Steel Inst., 1902, No. 1, page 188). Moissan obtained in the electric furnace a definite carbide of molybdenum, Mo_2C ("The Electric Furnace," 1904, page 105). Guillet, on investigating a series of molybdenum steels containing up to about 15 per cent. molybdenum, comments on their red-shortness (*Revue de Métallurgie*, 1904, page 390, *see* page 630 of present Report).

E. Vigouroux found four compounds of iron and molybdenum,

corresponding to the formulæ Fe_2Mo, Fe_3Mo_2, FeMo, and $FeMo_2$ (*Nature*, vol. lxxiii, 1906, page 600).

In addition to these, T. Swinden, Sheffield, has published a research on "Carbon and Molybdenum Steels" (Carnegie Scholarship Memoirs, vol. iii, 1911, pages 66–124). With one exception, the Papers referred to in the foregoing bibliography only touch the fringe of the real question at issue. Dr. Swinden's Paper, however, will for all time remain a storehouse of knowledge of the influence of molybdenum on steel up to a certain point. That he failed to reach the goal of definite conclusion is not the fault of the indefatigable and comprehensive investigations he so patiently and accurately carried out, but of circumstances he could not reasonably be expected to forecast, and which the Authors evaded, perhaps more by luck than management, as will be seen later on in this Report.

Hilpert and Ornstein obtained a series of carbides by heating powdered metallic molybdenum with methane. At 800° C. (1,472° F.) they found the composition varied from MoC to Mo_2C_3, but at 1,000° C. (1,832° F.) they obtained Moissan's carbide Mo_2C (*Chemical News*, 23rd August 1913, page 96).

The Authors' Molybdenum Steels.

Method of Manufacture.—The steels were manufactured in the ordinary commercial way in the experimental steel works of the University of Sheffield by the white crucible process with coke fuel. The materials used were Swedish "Lancash" bar-iron, Swedish white iron, and commercially pure molybdenum metal, all charged and melted together. A few minutes before teeming, small quantities of metallic manganese and aluminium were added. The ingots, weighing about 36 lb. each, were cast into moulds about 2 inches square. The cold ingots were re-heated and hammered into bars ¾ inch round. All hammered soundly,* but, as the

* The red-shortness observed by Blair, Mathews, and Guillet and Portevin was obviously due to fatal quantities of dissolved oxygen derived from the imperfectly reduced molybdenum metal employed in making their alloys.

molybdenum increased, an increase in hardness was observed by the hammerman, who also reported the evolution from the yellow-hot surfaces of the higher molybdenum ingots of yellowish-white fumes, no doubt MoO_3 which deposited as a sublimate on the hammer and tongs.

Method of Annealing.—The bars were annealed with a batch of files by gradually heating in a gas-fired furnace for a period of about 8 hours till a temperature of nearly 800° C. was reached. They were kept at about this heat for an hour and were then cooled down for a period of about 24 hours.

Chemical Analysis.—The chemical compositions of the series are embodied in Table 1 (page 632), the analyses being made on the last turnings from the carbide bars.

Mechanical Tests. Static Results.—The tensile test-pieces were turned from the annealed $\frac{3}{4}$-inch round bars to 2 inches parallel and 0·564 inch diameter, or $\frac{1}{4}$ square inch in area. The figures registered on a 50-ton Buckton single-lever machine are set forth in Table 2 (page 632).

All the tensile tests give similar results, excepting the low yield-point of 1531A and the distinctly higher maximum stresses registered by steels 1525A and 1526A.

Alternating Results.—The dynamic tests were made on an Arnold stress-strain machine under standard conditions, namely, on polished test-bars 6 inches long and $\frac{3}{8}$ inch diameter; the vertical distance from the zero of stress to the plane of maximum stress was 3 inches; the deflection at the zero of stress was $\frac{3}{8}$ inch a side; the rate of alternation being 650 per minute. The results registered are embodied in Table 3 (page 633).

The excessively poor results set forth in Table 3 fully confirm Dr. Swinden's conclusion that annealing seriously deteriorates the mechanical properties of molybdenum steels.

TABLE 1.

Number of Steel.	C.	Mo.	Si.	Mn.	P.	S.	Al.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
1531A	0·78	2·43	0·078	0·25	0·018	0·026	0·01 or under.
1530A	0·75	4·95	0·066	0·24	0·017	0·031	
1529A	0·71	10·15	0·071	0·23	0·016	0·036	
1525A	0·79	15·46	0·084	0·22	0·016	0·042	
1526A	0·82	20·70	0·098	0·21	0·017	0·046	

TABLE 2.

Number of Steel.	C.	Mo.	Yield-Point.	Maximum Stress.	Elongation on 2 inches.	Reduction of Area.	Fracture.
	Per cent.	Per cent.	Tons per sq. inch.	Tons per sq. inch.	Per cent.	Per cent.	
1531A	0·78	2·43	25·24	45·80	15·6	29·1	V. F. C.[1]
1530A	0·75	4·95	38·28	49·32	11·6	19·9	F. C. R.[2]
1529A	0·71	10·15	38·84	49·16	11·6	23·5	R. C. C.[3]
1525A	0·79	15·46	41·00	55·26	14·5	24·9	S. C. R.[4]
1526A	0·82	20·70	39·64	53·72	13·6	19·3	F. C.[5]

[1] Very fine crystalline. [2] Fine crystalline. [3] Rather coarse crystalline.
[4] Somewhat crystalline. Radial. [5] Fine crystalline.

Lathe Report.—The turning report states that no difference was noticed in the turning characteristics of the five steels. All were found to be slightly hard but tough. The word "tough" has reference to the capabilities of the steels to turn off in long spirals from the cutting edge of the turning tool.

Method used for Separating the Carbides.—The isolation of the carbides was carried out essentially as described for the determination of the Carbides of Tungsten Steels.* It was found, however, that

TABLE 3.

Steel No.	Carbon.	Molybdenum.	Alternations endured.		
			1st Test.	2nd Test.	Mean.
	Per cent.	Per cent.			
1531A	0·78	2·43	96	100	98
1530A	0·75	4·95	32	46	39
1529A	0·71	10·15	44	56	50
1525A	0·79	15·46	64	52	58
1526A	0·82	20·70	32	42	37

with steels high in molybdenum, so stable was the double carbide obtained, that within wide limits the strength of the electrolyte and the current density per square inch of anode were matters almost of indifference. For instance, hydrochloric acid of specific gravity 1·04 with a current density of 1·25 amps. per square inch gave practically the same results as those obtained with an acid of specific gravity 1·02 and a current density of 0·18 amp. The electrolysis throughout was therefore conducted under the conditions last named. The results obtained are embodied in Table 4, and shown graphically in Fig. 1 (page 636).

* Proceedings, I.Mech.E., 1914, page 223 *et seq.*

TABLE 4 (*continued on opposite page*).

Steel No.	Carbon in Steel.	Molybdenum in Steel.	Amount of Steel Dissolved.	Weight of Carbide Residue obtained.	Percentage of Total Molybdenum in Residue.	Percentage of Total Carbon in Residue.
	Per cent.	Per cent.	Grammes.	Grammes.		
1531A*	0·78	2·43	7·476	1·0028	95·70	95·61
1531A*	0·78	2·43	6·876	0·9159	96·02	93·40
1531A†	0·78	2·43	6·890	0·8942	94·10	91·35
Mean	0·78	2·43	7·081	0·9376	95·27	93·45
1530A	0·75	4·95	7·3626	0·8682	77·78	85·82
1530A	0·75	4·95	7·3754	0·8625	78·54	83·89
Mean	0·75	4·95	7·3690	0·8653	78·16	84·85
1529A	0·71	10·15	8·5620	1·5794	97·88	94·54
1529A	0·71	10·15	8·5190	1·5343	95·04	94·08
Mean	0·71	10·15	8·5405	1·5568	96·46	94·31
1525A	0·79	15·46	8·7680	2·3028	99·65	95·10
1525A	0·79	15·46	8·9280	2·2265	94·75	90·61
Mean	0·79	15·46	8·8480	2·2646	97·20	92·85
1526A	0·82	20·70	10·0882	3·0496	87·16	94·41
1526A	0·82	20·70	10·0884	3·0582	88·04	94·62
Mean	0·82	20·70	10·0883	3·0389	87·60	94·51

* Fe and Mo determined by the volumetric process described in the chemical section.

† Fe and Mo estimated by the ordinary gravimetric separation with NaHO, the molybdenum being weighed as Lead Molybdate.

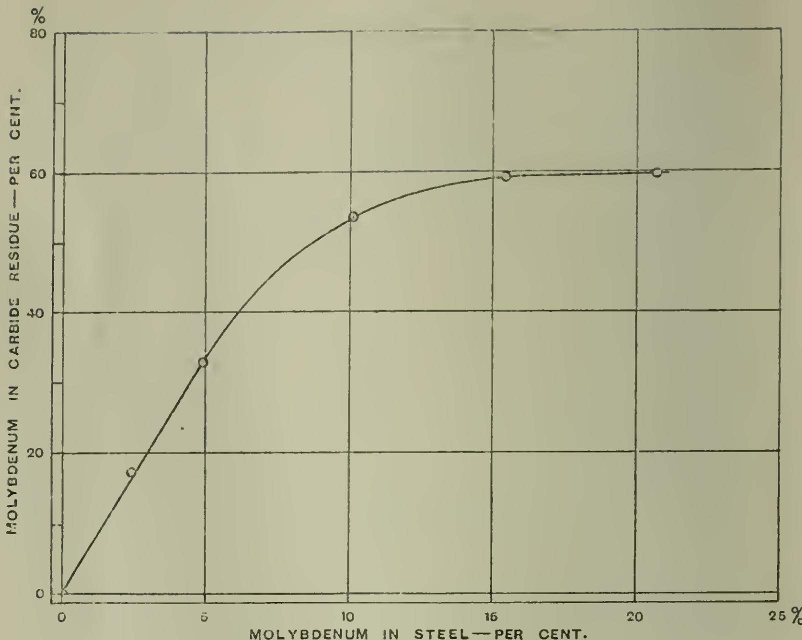
TABLE 4 (*concluded from opposite page*).

Analysis of Carbide Residue.			Corresponding to the Formula.	Theory.		
C.	Fe.	Mo.		C.	Fe.	Mo.
Per cent.	Per cent.	Per cent.		Per cent.	Per cent.	Per cent.
5·56	75·21	17·34				
5·47	75·46	17·54				
5·49	75·34	17·62				
5·51	75·34	17·50	$6\ Fe_3C + Fe_3Mo_3C$	5·43	75·94	18·63
5·46	61·81	32·66				
5·38	61·28	33·25				
5·42	61·54	32·96	$7\ Fe_3C + 3\ Fe_3Mo_3C + 2\ C$‡	5·37	62·43	32·20
3·64	41·92	53·86				
3·71	42·23	53·56				
3·67	42·08	53·71	$Fe_3C + 3\ Fe_3Mo_3C + C$§	3·76	42·04	54·20
2·86	37·00	58·66				
2·87	36·88	58·74				
2·865	35·94	58·70	$Fe_3C + 8\ Fe_3Mo_3C$	2·77	38·40	58·80
2·56	37·40	59·67				
2·56	37·21	60·12				
2·56	37·30	59·90	Fe_3Mo_3C	2·56	35·84	61·60

‡ Resulting from the internal electrolytic decomposition of some of the electropositive Fe_3C in the true formula $3\ Fe_3C + Fe_3Mo_3C$ containing C 4·76, Fe 66·67, Mo 28·57 per cent.

§ Resulting from the decomposition of some Fe_3C in the true formula $2\ Fe_3C + 3\ Fe_3Mo_3C$; C 3·40, Fe 47·60, Mo 49·00 per cent.

FIG. 1.



The ratios in Table 4 are set forth in Table 5 and plotted in Fig. 2.

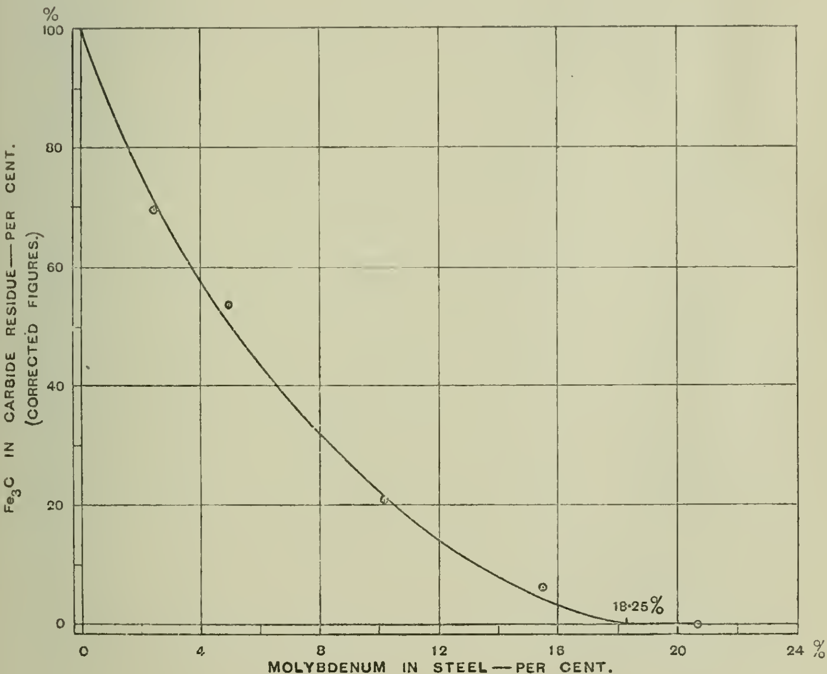
TABLE 5.

Percentage Ratios of Fe_3C and Fe_3Mo_3C.

Molybdenum in Steel.	Fe_3C in Residue.	Fe_3Mo_3C in Residue.
Per cent.	Per cent.	Per cent.
2·45	69·76	30·24
4·95	53·57	46·43
10·15	20·41	79·59
15·46	6·12	93·58
20·70	0·00	100·00

It will be seen that, at about 18·25 per cent. of molybdenum, free carbide of iron disappears and a double carbide of iron and molybdenum obtains, which, expressed in its lowest terms, corresponds to the formula Fe_3Mo_3C, and has been so written in Table 4. It is, however, probable that the constitutional formula of this remarkable compound is $Fe_6Mo_6C_2$.

FIG. 2.



Ferro-molybdenum carbide is obtained as a fine grey powder insoluble in strong boiling hydrochloric acid solution. It is not attracted by the magnet, whereas the residue from steel 1531A of formula 6 $Fe_3C + Fe_3Mo_3C$ was found to be strongly magnetic. The remarkable chemical stability of the double carbide under electrolysis is shown by the results of experiments made on steel No. 1526A containing 0·82 per cent. carbon and 20·70 per cent. molybdenum in Table 6 (page 638).

TABLE 6.

Specific Gravity of HCl used.	Current density amps. per sq. in. of anode.	Amount of Steel Dissolved.	Weight of Carbide Residue obtained.	Percentage of Total Molybdenum in Residue.	Percentage of Total Carbon in Residue.	Analysis of Carbide. Residue.			Theory.		
						C.	Fe.	Mo.	C.	Fe.	Mo.
		Grammes.	Grammes.			Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
1·04	1·25	5·8434	1·7515	86·86	99·08	2·71	37·52	59·82	2·56	35·84	61·6
1·02	0·18	8·9360	2·6812	86·48	96·83	2·65	37·60	59·68			

TABLE 7.

Two of Dr. Swinden's Experiments.

Mark.	Composition of Steel.		Analysis of Carbide.			Corresponding approximately to formula	Theory.		
	C.	Mo.	C.	Fe.	Mo.		C.	Fe.	Mo.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.		Per cent.	Per cent.	Per cent.
11	0·865	4·002	5·47	69·00	25·53	$8\,Fe_3C + 2\,Fe_3Mo_3C + C$ *	5·54	70·30	24·16
16	0·775	7·847	3·60	56·62	39·78	$3\,Fe_3C + 2\,Fe_3Mo_3C$	4·05	56·91	39·04

* Due to the internal electrolytic decomposition of some Fe_3C in the true formula $9\,Fe_3C + 2\,Fe_3Mo_3C$ = C 5·16, Fe 72·3, Mo 22·54 per cent.

Methods employed for the Analysis of Carbides.—The fact that molybdic oxide in sulphuric acid solution is quantitatively reduced to the sesquioxide by passing the solution through a column of amalgamated zinc was established by Randall.* It has also been shown by Edgar † that such solutions are not reduced at all by sulphur dioxide. As ferric salts are quantitatively reduced by both of these reagents to the ferrous condition, the determination of iron and molybdenum occurring together in the same solution can be readily effected. The following method, which was thoroughly tested by means of synthetic mixtures of varying and known proportions of iron and molybdenum, was finally used for the analysis of the carbide residues.

The residue was first treated with concentrated hydrochloric acid, which exerted no appreciable action even when heated; the addition of a few drops of concentrated nitric acid to the hot solution resulted at once in complete decomposition of the carbides, accompanied in, at any rate, two instances in the lower molybdenum range by the separation of carbonaceous matter. If perfect solution resulted, 5 cm^3 of concentrated sulphuric acid were added, and the mixture slowly evaporated until thick fumes of sulphur trioxide were evolved plentifully. If carbonaceous matter separated, it was filtered out, after dilution, washed and ignited. The residue thus obtained, less than a milligram in weight in each case, was added to the filtrate which was taken to SO_3 fumes as before. The residue was taken into solution in warm water, a solution of potassium permanganate added until a permanent colour was obtained, then dilute ammonium hydrate until a slight permanent precipitate was formed, and finally excess of a saturated aqueous solution of sulphur dioxide. The solution was slowly brought to the boiling point, and when colourless, or nearly so, indicating complete reduction of the iron, was treated with about $2 \cdot 5$ cm^3 of concentrated sulphuric acid for each 100 cm^3 of solution. When the sulphur dioxide was completely expelled by boiling

* American Journal of Science, vol. xxiv, page 313.

† *Ibid.*, vol. xxv, page 332.

(assisted by the passage of a vigorous current of carbon dioxide), the solution was titrated with a decinormal solution of potassium permanganate, whereby the iron was determined.

The titrated solution was then cooled to room temperature, and passed through a Jones reductor of amalgamated zinc, being preceded by 100 cm^3 of $2 \cdot 5$ per cent. sulphuric acid, and succeeded by the same amount of the reagent, followed finally by 150 cm^3 of water. The reduced solution and washings were received in a pressure flask attached to an aspirator or fitter pump, and containing 20 cm^3 of a solution of ferric alum made by dissolving 125 grams of the solid in 1,000 cm^3 of $2 \cdot 5$ per cent. sulphuric acid. The liquid was then titrated again with permanganate, the amount of which, less the former reading, gave that due to a reduction from MoO_3 to Mo_2O_3, from which the actual weight of molybdenum is calculated.

As a check on the above method, the carbide residue in one case was decomposed as above, the acid solution run in drops into a solution containing a large excess of sodium hydrate, and the ferric hydrate filtered out. This was re-dissolved in hydrochloric acid, re-precipitated in the same way, and washed.

The molybdenum in the combined alkaline filtrate was precipitated as lead molybdate and the iron in the residue determined volumetrically after dissolving from the filter. (*See* 1531A^3, Table 4, page 634.)

In Dr. Swinden's series of molybdenum steels already referred to in the bibliography, taking two steels marked by him 11 and 16, which are capable of reasonable comparisons with two of the Authors' alloys, the results obtained by Swinden calculated with the Authors' formula are embodied in Table 7 (page 638).

Thus the accuracy of Dr. Swinden's analytical results (with the single exception of the carbon of No. 16, which theoretically is decidedly low) is confirmed by the Authors' results obtained from somewhat similar steels containing, however, respectively, $4 \cdot 95$ and $10 \cdot 15$ per cent. molybdenum. Had the Authors stopped at about 8 per cent. molybdenum, Dr. Swinden's highest percentage, they would have found themselves in exactly the same difficulty as that

encountered by him in interpreting his results. Fortunately, the Authors carried their molybdenum beyond the complete replacement point of Fe_3C, and so obtained the key to the position by isolating a pure double carbide of iron and molybdenum, thus finding a reliable datum point for their calculations. (*See* Appendix II, page 650.)

Is the Carbon in quenched Steel in solid Solution as Carbon or as Carbide?—In the Journal of the Iron and Steel Institute, No. 1, 1910, page 176, the Authors showed that a hard steel containing 1·07 per cent. carbon and 13·38 per cent. manganese, in which, from the microstructure (*see* Photomicrograph No. 3, Plate VIII, of the Journal above quoted), the carbon in some form was obviously mainly in solid solution, gave on electrolysis about 75 per cent. of the total carbon in the form of a true double carbide of iron and manganese (3 Fe_3C, Mn_3C).

On the other hand, quenched carbon steel, containing about 0·9 per cent. carbon, yields on electrolysis a flocculent carbonaceous residue containing only about 1 per cent. Fe_3C. This must be due either to the carbon existing in a solid solution in the elementary condition, or to the dissolved carbide being in such a fine state of division that its iron dissolves in the electrolyte. The remarkable chemical stability of the double carbide of iron and molybdenum found in this research suggested to the Authors that it would be well to make some experiments on drastically hardened bars of the double carbide steel, containing 0·82 per cent. carbon and 20·70 per cent. molybdenum. The results obtained with the standard electrolyte and current density already described will be found in Table 8 (page 642).

An inspection of the results in Table 8 will show that, in these drastically quenched steels, an average of about 61 per cent. of the total carbon was obtained from solid solution, and that the average composition of the residues approximated the formula Fe_3Mo_3C, hence it may now be taken as settled that the carbon in hardened steels exists in the form of carbide in solid solution.

TABLE 8.

Electrolysis Experiments on four quenched bars of Steel No. 1526 *containing* 0·82 *per cent. Carbon and* 20·70 *per cent. Molybdenum.*

Heat Treatment.	Amount of Steel Dissolved.	Weight of Carbide Residue obtained.	Percentage of Total Molybdenum in Carbide Residue.	Percentage of Total Carbon in Carbide Residue.	Analysis of Carbide Residue.		
					C.	Fe.	Mo.
First Pair.	Grammes.	Grammes.			Per cent.	Per cent.	Per cent.
Heated to about 1,200° C. (2,192° F.) *in vacuo* and quenched out in water of 40° C. (104° F.).	8·5521	1·9006	62·94	69·66	2·57*	38·21	58·62
	7·9830	1·3198	47·30	44·35	2·20*	40·34	57·21
Second Pair.							
Heated to about 1,200° C. *in vacuo* and quenched out in whale oil of 15° C. (59° F.).	8·4210	1·8400	63·57	53·96	2·55*	36·54	60 24†
	8·6498	2·0436	68·89	74·61	2·59*	36·75	60·37†

* Theory, C 2·56 per cent., Fe 35·84 per cent., Mo 61·60 per cent.

† These carbides were non-magnetic.

The transformation of Ferro-molybdenum Pearlite into its Hardenite. —As will be seen in the photomicrographic section, the discovery of true ferro-molybdenum steels has naturally added three new micro-constituents to the annals of steel metallurgy, namely, ferro-molybdenum pearlite, ferro-molybdenum hardenite, and ferro-molybdenum cementite. The set of experiments recorded in Table 9 shows roughly the thermal amplitude of the transformation of ferro-molybdenum pearlite into its corresponding hardenite. The trials were made on disks of steel $\frac{5}{8}$ inch diameter by $\frac{1}{4}$ inch

TABLE 9.

Quenching and File Hardness Experiments on Steel No. 1525A, *containing* 0·79 *per cent. Carbon and* 15·46 *per cent. Molybdenum.*

The ratio of the Carbides in this Steel is Fe_3Mo_3C 93·58 and Fe_3C 6·12 per cent.

Water Quenching Temperatures.		File and Hammer Test Indications.
Degrees C.	Degrees F.	
855	1,571	Filed easily; quenched disks not brittle.
990	1,814	Filed; disks not brittle.
1,060	1,940	Filed with difficulty; disks rather brittle.
1,125	2,057	Dead hard to file; disks very brittle.
1,180	2,156	Dead hard to file; disks very brittle.

thick, heated in a salt bath to the various temperatures and quenched out in cold water.

Table 9 thus shows very clearly that the transformation of ferro-molybdenum pearlite to its hardenite somewhat coincides with the transformation of tungsten pearlite to tungsten hardenite.* The transformation seems to begin somewhere upwards of 900° C. (1,652° F.), say at 925° C. (1,697° F.), and is evidently about completed at 1,100° C. (2,012° F.), the amplitude of the transformation being roughly about 175° C. (315° F.) (for an early stage of this transformation, *see* Fig. 4, Plate 9).

* Proceedings, I.Mech.E., 1914, page 244.

Absorption and Recalescence Curves.—These curves will be included in a separate Paper dealing with the whole of the steels in the Authors' double carbides research series. It may, however, be here remarked that the Authors have already published sufficient absorption and recalescence data to prove that the hardening of steel is unconnected with the alleged allotropy of iron. In a Paper on "The Chemical and Mechanical Relations of Iron, Vanadium and Carbon," published in the Journal of the Iron and Steel Institute, No. 1, 1912, page 225, the Authors showed, in the case of a vanadium steel containing 1·07 per cent. carbon and 10·30 per cent. vanadium, that on heating from 500 to 1,210° C. (932° to 2,210° F.), only the absorption point Ac_2 was presented, its maximum appearing at 826° C. (1,519° F.). On cooling from about 1,200° (2,192° F.) to 500° C. (932° F.), Ar_2 presented its top peak at 830° C. (1,526° F.), and its lower peak at 816° C. (1,501° F.). When the steel was quenched in cold water from temperatures of 850°, 1,000° and 1,050° C., it remained quite soft to the file. The reason for this was found in the fact that the carbon change-point Ac_1 took place at a white heat, say about 1,400 C. When quenched from this temperature, micrographically structureless vanadium hardenite was obtained, and it was found to be probably the hardest metallic substance known, being certainly as hard as topaz and possibly as hard as corundum—the latter is 9 on Moh's mineral scale, diamond, the hardest substance known, being 10. Unfortunately, vanadium hardenite, *per se*, seems to be too brittle to be of any practical use, a fact determined on the lathe, and reported to one of the Authors by an ex-student of Sheffield University, who is now metallurgist to a Sheffield steel firm. It may be, however, that this fault can be removed by suitable heat treatment. Upon this matter the Authors have not yet been able to find time to experiment.

General Survey of the Constitutions of the Four True Steels in their Normal and Hardened Conditions.—The approximate compositions of the pearlites and hardenites of the four true steels, namely, iron steel, vanadium steel, tungsten steel, and ferro-

TABLE 10.

Name of (True) Steel.	Approximate Saturation Points. Carbon Per cent.	Approximate Pearlite Formulæ of Saturated Steels.	Approximate Percentage Compositions of Saturated Steels.	Approximate Empirical Compositions of Hardenite (Saturated Solid Solutions).	Complete Displacement of Fe_3C by about	Temperature of Carbon Change-Points on Heating.	Thermal Amplitude of Change Range.
Iron	0·89	(21 Fe + Fe_3C)	Fe 87 Fe_3C 13	$Fe_{21}C$	——	About 729° C.	About 3° C.
Vanadium	0·83*	(72 Fe + V_4C_3)	Fe 94·5 V_4C_3 5·5	$Fe_{72}V_4C_3$†	4·70 per cent. V	About 1,400° C.	Unknown but small.
Tungsten	0·72	(26 Fe + WC)	Fe 88 WC 12	$Fe_{26}WC$†	11·28 per cent. W	Begins about 850°, complete about 1,100° C.	About 250° C.
Ferro-Molybdenum	0·71	(24 Fe + Fe_3Mo_3C)	Fe 70·5 Fe_3Mo_3C 29·5	$Fe_{24}Fe_3Mo_3C$†	18·25 per cent. Mo	Begins about 925°, complete about 1,100° C.	About 175° C.

* In the Journal of the Iron and Steel Inst. 1912, No. 1, pages 224–5, the Authors, in describing Photomicrograph No. 3, Plate XXIV, which has reference to a steel containing 0·93 per cent. C and 5·84 per cent. V, wrote: "This section consists largely of sorbitic vanadium pearlite overlaid, however, by irregular meshes apparently of vanadium ferrite—in other words, the steel is not saturated." It has since been found that the meshes are vanadium cementite and that the steel is really supersaturated.

† When the alloying element is in excess of the complete displacement point, this iron will be alloyed or combined with some vanadium, tungsten or molybdenum, as the case may be.

molybdenum steel, now known to metallurgical science, are set forth in Table 10.

From the foregoing constitutional Table, it is clear that all the four true steels therein formulated belong to a single genus, the individual members of which present startling differences. But throughout the series there is found a soft pearlite which, over a certain range of temperature, transforms to its hardenite. These hardenites probably vary in hardness from 7 to 9 on Moh's mineral scale—that is, from quartz to corundum. Their respective hardnesses are inherent properties of the respective definite solid solutions of their carbides, and beyond this nothing is known. Neither is it known why, relatively to the diamond or corundum, quartz is soft. Mineralogists have not yet discovered the molecular configurations which determine these differences. If the Authors may venture to bring home to the minds of the members of the Institution the astounding differences which may exist in the animate world in the members of one genus, the ornithological genus Erithacus may be quoted. There are three members of this genus, namely, the red-throated robin, the blue-throated robin and the nightingale. So in true steels there exist in the inanimate world, iron steel, vanadium steel, tungsten steel, and ferro-molybdenum steel, all members of one genus, in spite of their startling individual differences.

Practical Sheffield steel metallurgists who have been consulted by one of the Authors estimate from lathe and drill experiences that roughly the steel-hardening power of molybdenum is from two to three times as great as that of tungsten. Theoretically, according to the empirical data given in the hardenite column of Table 10, one atom of carbon is about 2·28 times as powerful in producing hardenite in true ferro-molybdenum steel as it is in forming the hardenite of true tungsten steel (*see* calculations in Appendix I). Thus theory and practice agree—when the theory is right. When theory and practice do not agree, theory is wrong. Unfortunately, molybdenum is much more erratic in its behaviour than tungsten, and the latter, though the less powerful element, still sits unshaken on its throne, because of its reliable behaviour. The Authors

present a clue in this research to the irregular behaviour of molybdenum by calling attention to the astoundingly poor mechanical properties of molybdenum steels compared with corresponding steels containing tungsten. Also it is shown in Table 9 (page 643) that high molybdenum steel quenched out at a proper hardening temperature is very brittle. It is therefore clear that so powerful a steel-producing element should be used sparingly, avoiding large percentages. With low percentages it undoubtedly exerts a beneficial influence on certain classes of steel, when used cautiously either *per se* or to replace about 2½ times its percentage of tungsten.

Points of Resemblance and of Difference between the Actions of Tungsten and Molybdenum on Steel.

Resemblances.—Molybdenum resembles tungsten only in the following item: the thermal transformation of its pearlite to hardenite presents in its thermal range a very considerable likeness to the transformation of tungsten pearlite to tungsten hardenite.

Differences.—The differences between annealed tungsten and molybdenum steels (both with reference to steels which are molybdenum steels in the sense that they contain molybdenum, or that they are true molybdenum steels containing over 18·25 per cent. molybdenum) are very remarkable. (*a*) Molybdenum does not, like tungsten, form a single carbide, but a most remarkable double carbide with iron. It is non-magnetic in spite of the large quantity of iron involved in its composition, and is of great chemical stability when attacked by the less oxidizing acids. (*b*) In their mechanical properties annealed molybdenum steels are distinctly inferior in ductility to corresponding tungsten steels when statically tested in tension, and their inferiority under alternating stresses is very marked.* (*c*) Tungsten carbide completely replaces carbide of iron when about 11·28 per cent. of the element is present. Molybdenum replaces free carbide of iron

* Proceedings, I.Mech.E., 1914, pages 231, 232.

when about 18·25 per cent. is present, but, unlike tungsten, it combines with a large proportion of the carbide of iron, forming a very stable double carbide. (Indeed, the major part of this double carbide can be recovered by electrolysis from its solid solution in hardened steels almost to theoretical formula.) (*d*) Unlike tungsten steels, molybdenum steels liberate their double carbide pure with a weak electrolyte and low current density. (*e*) Molybdenum does not appear within the limits tested by the Authors to form a definite molybdide of iron corresponding to the definite tungstide of iron Fe_2W, which begins to form when the tungsten reaches about 11·28 per cent.

Resemblances between Molybdenum and Vanadium.—As high vanadium facilitates the segregation of vanadium cementite, so very high molybdenum seems to cause ferro-molybdenum cementite to segregate more readily in annealed steels (*see* photomicrograph, Fig. 5, Plate 9). Ferro-molybdenum hardenite also resembles that of vanadium in brittleness when quenched above its complete transformation temperature.

MICROGRAPHIC ANALYSIS.

Photomicrograph Fig. 3, *Plate* 9 (1530A), C 0·75 per cent., Mo 4·95 per cent., etched with picric acid in alcoholic solution. The pale ground mass is electro-negative sorbitic ferro-molybdenum pearlite. The dark areas are segregated Fe_3C, which is electro-positive to the more stable ferro-molybdenum pearlite. There are also a few white areas apparently ferro-molybdenum cementite.

Photomicrograph, Fig. 4, Plate 9 (1525A), heated and quenched, C 0·79 per cent., Mo 15·46 per cent. Etched with picric acid in alcoholic solution. Dark ground mass, electro-positive ferro-molybdenum pearlite. White areas, electro-negative ferro-molybdenum hardenite (mixed with a small quantity of iron hardenite). This micro-section was quenched in cold water from a temperature of 990° C. (1,814° F.), and the pearlite to hardenite transformation has obviously taken place to a considerable extent.

Photomicrograph Fig. 5, Plate 9 (1526A), C 0·82 per cent., Mo 20·70 per cent. Etched in boiling sodium picrate. Dark areas, segregated ferro-molybdenum cementite, together possibly with some segregated Fe_3C. Ground mass, molybdeniferous ferrite and some ferro-molybdenum sorbitic pearlite in which the double carbide has not segregated.

Conclusion.—The Authors, having now completed their work on the double carbides of steel, again thank the Council for their financial help. They venture to suggest, however, that the unravelling of the varying mysteries of the Carbides of Tungsten and Molybdenum, Nickel and Cobalt, forms a record not unworthy of the traditions of that Institution under whose auspices Abel and Deering in 1885 placed in position the foundation stone of modern scientific steel metallurgy, namely, the definitely ascertained existence of the compound, carbide of iron Fe_3C, or a multiple thereof.

The Authors would also tender their sincere thanks to Mr. F. Ibbotson, B.Sc., B.Met., Senior Lecturer in Metallurgical Chemistry at the University of Sheffield, for his patient and accurate chemical work. Also to Mr. F. K. Knowles, B.Met., Senior Lecturer in Metallurgy in the University of Sheffield, for his always reliable services in connexion with the metallurgy, mechanical and heat treatment branches of the research. Also to Mr. F. C. Thompson, M.Met., B.Sc., Demonstrator in Metallography, for his help in connexion with the micrographic work, and also (in conjunction with Mr. L. Aitchison, M.Met., Demonstrator in Metallurgical Chemistry) for his careful work in checking the numerous calculations in chemical arithmetic involved. Finally, the Authors would thank Mr. J. Harrison, Engineer to the Metallurgical Department of Sheffield University, for the great care he has taken in preparing the numerous test-pieces required for the investigation, and in keeping clear their identity throughout.

The Paper is illustrated by Plate 9 and 2 Figs. in the letterpress, and is accompanied by two Appendixes.

APPENDIX I.

Calculations of the theoretical hardenite producing powers of carbon in true tungsten steel, and in true ferro-molybdenum steel respectively :—

$$\left.\begin{array}{l} C = 12 \\ C = 12 \end{array}\right\} = \begin{array}{l} 184 \text{ W} \\ 456 \text{ Fe}_3\text{Mo}_3. \end{array}$$

Hence the gross power of $Fe_3Mo_3 = \frac{456}{184} = 2 \cdot 48$ times that of W.

Then the actual power of $Fe_3Mo_3 = 2 \cdot 48 - 0 \cdot 20$ (for two extra atoms of Fe converted into W hardenite) or $2 \cdot 28$ times the power of W.

Atomic weights C = 12, Fe = 56, W = 184, Mo = 96.

Formula for tungsten hardenite $Fe_{26}WC$, for ferro-molybdenum hardenite $Fe_{24}Fe_3Mo_3C$.

APPENDIX II.

In view of the low carbon result in the carbide from bar No. 16, the Authors, to clear this matter up, communicated with Dr. Swinden, and he kindly sent them a piece of the original rolled and reeled $\frac{5}{8}$-inch diameter bar. This was moderately annealed, and the analysis was made on the last turnings from the $\frac{3}{8}$-inch diameter carbide bars. The results obtained by electrolysis are embodied in Table 11.

TABLE 11 (*continued below*).

Analysis and Electrolysis of Dr. Swinden's Bar No. 16.

The bars were electrolyzed for 15 hours with a current density of 0·18 amp. and a voltage of 1·0 rising to 1·6 between the extreme terminals. The specific gravity of the dilute hydrochloric acid electrolyte was 1·02.

Steel No.	Carbon in Steel.	Molybdenum in Steel.	Weight of Steel Dissolved.	Weight of Carbide Residue obtained.	Percentage of Total Molybdenum in Carbide Residue.	Percentage of Total Carbon in Carbide Residue.
	Per cent.	Per cent.	Grammes.	Grammes.		
16	0·74	7·92	8·5642	1·4515	92·72	95·01
16			8·5410	1·4412	92·92	93·69

TABLE 11 (*concluded from above*).

Steel No.	Analysis of Carbide Residue.			Corresponding to the Formula	Theory.		
	C.	Fe.	Mo.		C.	Fe.	Mo.
	Per cent.	Per cent.	Per cent.		Per cent.	Per cent.	Per cent.
16	4·14	51·40	43·21	$4\ Fe_3Mo_3C + 4\ Fe_3C + C$ *	4·15	51·61	44·24
16	4·11	51·52	43·62				

* Resulting from the internal electrolytic decomposition of one molecule of electro-positive F_3C from the true formula $4\ Fe_3Mo_3C + 5\ Fe_3C$ = C 3·90, Fe 54·54, Mo 41·55 per cent.

THE CAUSE AND EFFECT OF "GHOST LINES" IN LARGE STEEL FORGINGS.

By J. O. ARNOLD, D.Met., F.R.S.,
Professor of Metallurgy in the University of Sheffield.

During the past twenty years the Author has occasionally been requested to investigate the phenomena of "ghosts" in forgings from large steel ingots, ranging in weight from about 40 to 80 tons. An exact knowledge of the method of formation and the nature of "ghost lines" is a matter of great importance both to steel metallurgists and to naval engineers.

In 1894 the Author and Mr. Rudolf Leffler, Associate in Metallurgy of the University of Sheffield, made a pioneer investigation of the nature of the "ghost lines" in a large steel forging made from a 40-ton ingot, from the upper portion of which about 30 per cent. had been cut away to scrap. During turning operations the "ghost lines" in this forging, which were of a very decisive character, showed up white and in slight relief against the steel-grey colour of the mass of the turned forging. When exposed to the sulphurous atmosphere of Sheffield over the week-end, the white "ghost lines" turned light brown owing to oxidation. By means of a fine and sharp engraver's tool a number of the "ghost lines" were dug out, and similar minute excavations were made on

parallel lines on portions of the forging free from ghosts. Of course, the shavings taken along the "ghost lines" were, to use an Irishism, contaminated with some steel free from ghosts. The two sets of shavings on analysis registered the following figures:—

Analysis of Ghost-Free Portions of the Forging.

	Per cent.
Carbon	0·320
Silicon	0·080
Manganese	0·680
Sulphur	0·020
Phosphorus	0·035

Analysis of Shavings from Portions of Forging Showing Ghosts.

	Per cent.
Carbon	0·380
Silicon	0·310
Manganese	0·920
Sulphur	0·045
Phosphorus	0·050

The foregoing figures show that the inclusion in the steel shavings of some "ghost lines" had raised the carbon 19, the silicon 287, the manganese 35, the sulphur 125, and the phosphorus 44 per cent., the ghost-free figures being taken as 100 per cent.

Micrographic Examination.—The microstructure of the "ghost lines" showed the presence of excessive streaks of dove-grey sulphide of manganese, and of excessive carbon in the form of troostitic pearlite, and the latter caused the ghost to etch dark brown, indeed almost approaching black. Greenish vitreous streaks of Stead's silicate of manganese, or possibly bisilicate of manganese and aluminium, were also present, causing the notably high silicon and manganese in the steel shavings containing the ghost.

It is now obvious that the elements showing true segregation were carbon, sulphur, and phosphorus, whilst the silicates probably formed while the steel was running down the lander from the furnace, and were incidentally involved in the steel. The Author

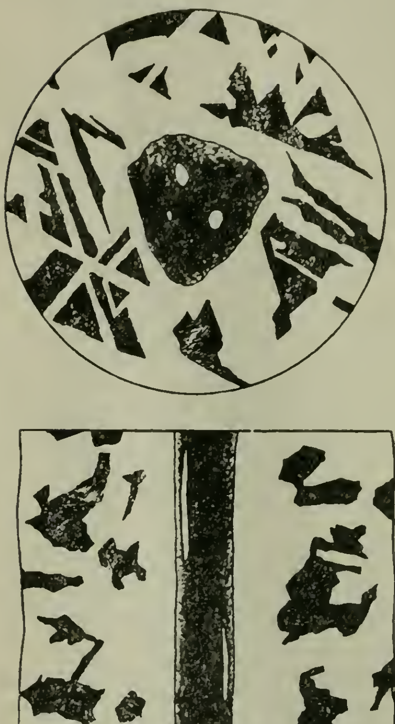
will hereinafter exhibit titanic ghosts almost free from silicates. In these circumstances it is most unfortunate that the true migratory elements are usually included in the general and inaccurate term "slag inclusions." The latter are either accidental or incidental, whilst sulphide of manganese is an absolutely normal and unavoidable constituent of all steels, excepting high-speed tool steels, in which the sulphur exists in solid solution as non-injurious sulphide of tungsten (WS_2), a fact ascertained in a semi-private but somewhat extensively circulated research, the results of which were issued by the Author about a year ago under the new copyright regulations. A printed copy of the research was deposited officially by the Registrar in the archives of Sheffield University.

The Genesis of "Ghost Lines."—On 10th April 1908 the Author, at the request of the late Sir William H. White, read in London at the Meeting of the Institution of Naval Architects, a Paper entitled "Factors of Safety in Marine Engineering." An extract from this, headed "On Ghost Lines," is produced below, together with some of the photomicrographs illustrating the Paper above referred to:—

On Ghost Lines.—In a big ingot, irrespective of the liquated and scrapped upper third, in parts of which the phosphorus, for instance, may exceed one per cent., there is always more or less a segregation of the mobile elements, carbon, sulphur, and phosphorus to a series of centres. Investigations on the "Diffusion of Elements in Iron," carried out at the Sheffield University College, and published in the Journal of the Iron and Steel Institute, No. 1, 1899, indicated the mobility of carbon to be about five times as great as that of sulphur, phosphorus, and nickel. The upper photomicrograph in Fig. 1 (page 656) shows a dark etching nodular segregation area. This consists of iron containing an undue proportion of (*a*) an isomorphous mixture of the double carbides of iron and manganese ($x Fe_3C$, $y Mn_3C$); (*b*) dissolved phosphide of iron (Fe_3P); (*c*) small segregated irregular globules of sulphide

of manganese (MnS). On forging the ingot the angular or martensitic structure is broken up, whilst the nodular segregate is drawn out into a dark-etching rod (*see* also micrograph,

FIG. 1.—*Segregated Area in Ingot.*



Carbonized Ghost
in Manufactured Forging.
Magnified 125 diams.

FIG. 2.

Sectional Elevation and Plan of Decarburized Ghost Line in Annealed Forging.

Magnified 37½ diams.

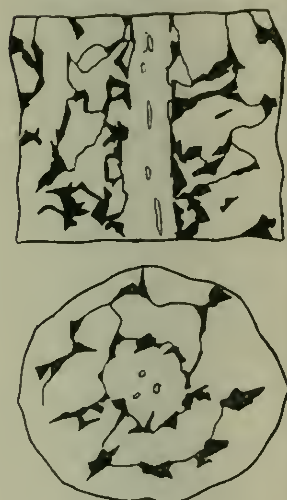


Fig. 1). In such a forging the elongated segregation, which is relatively hard, is in turning operations jumped by the tool, leaving in faint relief a relatively white line,* hence the turner's somewhat

* A decarburized "white ghost" is relatively soft and is "dragged" by the tool leaving a faint depression.

far-fetched name "ghost." During the prolonged cooling at a low red heat, the carbonized ghost becomes decarburized, the dissolved phosphide of iron seeming to expel the hardenite (transformed pearlite) to the edges of the "ghost line," * the final product being the decarburized "ghost line," as exemplified in Fig. 2. Here the ghost has become essentially a broken and irregular cylinder of pearlite, filled with pale brown etching ferrite containing emulsified phosphide of iron, through which are scattered short rods of dove-grey sulphide of manganese.

The Mechanical Effect of Ghosts on the Engineering Efficiency of Large Marine Propeller-Shafts.—The Author was requested to decide whether or not the presence of moderately large "ghost lines" in a propeller-shaft, forged from the lower end of an 80-ton ingot, was mechanically dangerous under torsional stresses and strains, and he has been permitted to quote the substance of his report:—

Report on "Ghost Lines" in Large Propeller-Shaft.—I examined in the lathe a propeller shaft which I was told was for a cruiser and had been forged from an ingot weighing about 80 tons. I examined the turned shaft for "ghost lines," which are always present in large masses of forged steel. They were clearly visible, especially on the coned end. As you had requested me to ascertain the exact influence of these "ghost lines" on the mechanical properties of the steel, it was necessary to cut up the end of this shaft for experimental purposes. The shaft was sampled so as to get sets of test-bars visually containing well-marked "ghost lines," all such samples being marked "B," and similar sets exhibiting hardly any "ghost lines," these latter samples being marked "G." On this basis two pairs were taken for tension tests, two pairs for torsion tests, and six pairs for alternating-stress tests. From these test-bars seven pairs of sections were cut out for microscopical examination.

On the Nature of "Ghost Lines."—The results of recent research in the Metallurgical Department of Sheffield University indicate that ghosts are formed in large ingots by segregation in the following manner: Just before the ingot solidifies, a definite alloy of iron with sulphide of manganese freezes out from solution and segregates to a series of centres. These frozen masses

* This curious action of dissolved phosphide of iron was first pointed out by Dr. J. E. Stead, F.R.S.

seem to form nuclei, around which gather the migratory elements of steel, namely, carbon, sulphur, phosphorus, and, if present, nickel. Thus is obtained a more or less globular compound segregate, which is somewhat variable in composition, but with an average constitution approximately as follows:—

Composition of Main Mass of Ingot.		Composition of Ghost Globules.	
	Per cent.		Per cent.
Carbon	0·30	Carbon	0·39
Sulphur	0·04	Sulphur	0·12
Phosphorus . . .	0·04	Phosphorus . . .	0·10

On forging, the ghost globules relatively high in carbon, sulphur, and phosphorus are drawn out into strings, which, on turning, exhibit themselves as the well-known "ghost lines." In an annealed shaft such as that now under consideration, these "ghost lines" are always "white" ghosts when viewed under the microscope. The "ghost line" is, in fact, a streak of iron free from carbon, but containing in solid solution, and hence invisible, the phosphide of iron, which has expelled the carbon to the edge of the ghost. The sulphur is scattered through the iron of the ghost in the form of dove-grey streaks of manganese-sulphide. I may point out that "ghost lines" can never be eradicated from large masses of forged steel until metallurgical science has entirely eliminated sulphur from steel. This, I fear, will not happen in our time, if ever.

On Plate I* will be seen three photomicrographs, Nos. 1, 3 and 7 of the "B" series. Photomicrograph B1 shows a well-marked ghost practically free from carbon, but exhibiting several streaks of manganese sulphide. Photomicrograph B3 shows a similar structure, but with less marked ghosts. Photomicrograph B7 is practically free from "ghost lines," presenting only crystals of pale-etching iron (ferrite) and dark-etching finely laminated steel areas (pearlite). On Plate II will be found three photomicrographs of the "G" series, i.e., the set of pieces which externally for the time being showed no ghosts. Photomicrograph G5 exhibits the largest streak of manganese sulphide observed in the whole of the fourteen sections examined. It should, however, be remembered that the actual length of this streak is only one-hundredth of the length shown in the photomicrograph. Photomicrograph

* The photomicrographs referred to in this Report are not illustrated in the Paper.

G4 shows an average ghost, while photomicrograph G3 is virtually free from ghosts, consisting only of pale ferrite (iron) and dark pearlite (steel).

The General Mechanical Influence of White Ghosts.—White ghosts, as I have already pointed out, are a succession of streaks of carbonless iron containing about 0·10 per cent. of dissolved phosphorus and about the same percentage of sulphur, the latter presented as visible streaks of sulphide of manganese. A rough and ready rule to convert the percentage of sulphur by weight into percentage of sulphide of manganese by volume is to multiply by 5, hence the volume percentage of manganese sulphide in ghosts generally is about 0·5 to 0·6 per cent. It should, however, be remembered that the volume of the alloy of iron and sulphide of the manganese which first froze out would constitute several per cent. of the mass of the ghost.

So far as my experience goes, "ghost lines" are little detrimental to the mechanical properties of structural steel, so long as the plane of stress is at right angles to the direction of the "ghost lines"—in other words, when the material is in tension, torsion, or under alternating stresses.

With a reasonable factor of safety (say 3½ to 1 on the elastic limit) I have never heard of a propeller-shaft breaking in tension or torsion, but always under alternating stresses, the plane of rupture being at right angles to the "ghost lines" and on the theoretical plane of maximum stress at the outboard end of the liner, say about one inch aft of the propeller boss. With such fractures ghosts have little or no connexion.

Investigation of the Mechanical Properties of the Shaft.

Static Tensile Tests.—All the test-pieces were 2 inches parallel, 0·564 inch diameter, 0·26 inch square area.

Mark.	Yield-Point.	Maximum Stress.	Elongation.	Reduction of Area.	Fracture.
	Tons per sq. in.	Tons per sq. in.	Per cent. on 2 in.	Per cent.	
4200 F G4	18·32	30·20	35·5	59·74	Fine grey granular.
4200 F G5	16·30	30·84	35·5	52·17	,, ,, ,,
4200 F B1	15·00	30·20	35·0	60·41	,, ,, ,,
4200 F B4	15·40	32·80	37·0	65·14	,, ,, ,,

The figures in the foregoing Table all denote a structural steel of very good quality and of generally even texture. Any slight variations are due to

the fact that in annealing such shafts the texture of the pearlite (steel area) always varies a little, some regions being somewhat more laminated and hence milder than others. Extensometer tests were taken on each test-bar, and a typical curve was plotted, in which the true elastic limit is indicated about 14 tons per square inch, and the yield, or breakdown point, at about 17 tons per square inch.

Static Torsion Tests.—All test-bars were 6 inches parallel, and 0·8 inch diameter, or 0·5 square inch in area.

Mark.	Stress endured in inch-lb.	Angles of rotation endured.	Remarks.
4200 F G7	7,721	1,745°	Previous to testing, a straight ink line was ruled along each test-bar.
4200 F G6	7,459	1,578°	The spirals on the fractured bars mark the torsional movement during the testing operations.
4200 F B5	7,647	1,909°	
4200 F B7	7,425	1,631°	(*See* example in Fig. 3, Plate 10.)

Dynamic or Alternating-Stress Tests.—The subjoined tests were made on an Arnold stress-strain machine under standard conditions, namely, burnished test-bars 6 inches long, by $\frac{3}{8}$ inch diameter; distance from zero of stress to plane of maximum stress 3 inches; deflection at zero of stress $\frac{3}{8}$ inch each way; rate of alternation 650 per minute. The results are embodied in the following Table. The grand means of each include twelve tests each.

Table of Dynamic Stress Tests (continued on next page).

Mark.	1st Test.	2nd Test.	Mean.	Grand Mean.
G1	254	258	256	
G2	258	230	244	
G3	250	252	251	246
$G1_2$	264	232	248	
$G2_2$	254	240	247	
$G3_2$	230	230	230	

Table of Dynamic Stress Tests (concluded from previous page).

Mark.	1st Test.	2nd Test.	Mean.	Grand Mean.
B2	282	254	268	278
B3	244	264	254	
B5	286	280	283	
$B2_2$	298	290	294	
$B3_2$	294	282	288	
$B5_2$	248	274	261	

Curiously enough, the samples selected as having marked "ghost lines" give better results. The tests present nothing remarkable, being such as are generally given by a shaft forged from a large ingot and subsequently moderately annealed. The absence of over-annealing in the sense of too slowly cooling, is evidenced by the stress-strain diagram already referred to.

Conclusion.—An examination of the fractures of the whole of the test-pieces, namely, eight in tension, eight in torsion, and forty-eight in alternation, exhibited at the respective points of rupture no signs of cracking or opening due to "ghost lines," or to any other cause. I am therefore of opinion that no risk would be incurred by putting similar shafts into the vessels building.

Examination of the Ghosts in a large Ingot as Cast.—Comparatively recently the Author had an opportunity quite unique in character of ascertaining the exact nature of unforged ghosts, some of which were about $\frac{5}{8}$ inch in diameter and 9 inches long. The details of the extraordinary circumstances in which these gigantic ghosts were obtained, to the number of perhaps 50, are as follows:—

A mild steel chrome-nickel ingot, weighing (together with its feeding head) about 57 tons, was being cast, and the casting was just completed when a burst-out occurred at the bottom. The time record is as follows:—Casting was commenced at 8.57 p.m., steel entered the feeding head at 9.23 p.m., and the casting was finished at 9.28 p.m. The burst-out occurred five minutes later at 9.33, but was stopped at about 9.35 p.m. When cold it was found that the ingot was hollow for 21 inches down, having "bled" about

17 tons of steel. The ingot was 60 inches octagon at the top by 46 inches octagon at the bottom, and 156 inches long. A sectional elevation and plan of the ingot is shown in Fig. 4 ($\frac{1}{40}$th full size). On cutting off the hollow portion of the ingot and then cutting

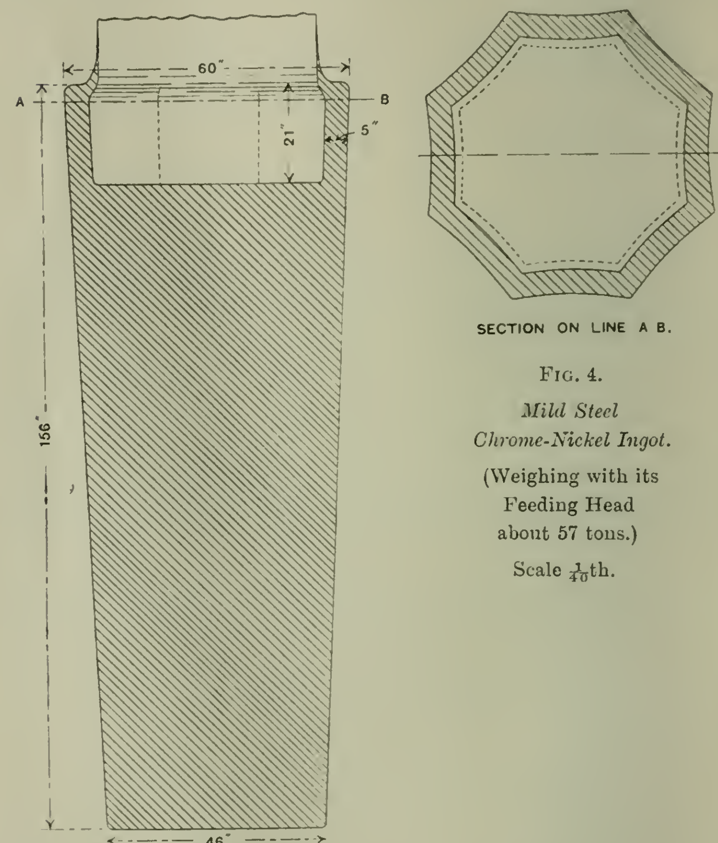


FIG. 4.
Mild Steel Chrome-Nickel Ingot.
(Weighing with its Feeding Head about 57 tons.)
Scale $\frac{1}{40}$th.

this portion longitudinally into four pieces, a most extraordinary discovery was made. In each octagonal angle was found a series of protruding frozen ghosts. In Fig. 7, Plate 11, will be seen a reproduction $\frac{1}{4}$ full size of these ghosts; the vertical line indicated the apex of this particular octagonal angle. With so much

material available it was easy to make an exhaustive chemical and microscopical examination of these ghosts; some of which were protruding to an extent of $\frac{3}{8}$ inch. The surfaces of the steel free from ghosts showed decisive projecting indications of octahedral crystallization. The ghosts seemed to have caught on the angle where the body of the ingot turns upward to the feeding head, seeming to have been mechanically trapped on what may be termed a series of metallurgical futtock shrouds.* A complete set of ghosts from one angle was chipped away flush with the main body of the solidified shell of the ingot and was carefully analysed. Drillings were also taken in a region free from ghosts, as indicated by the black disk in Fig. 7. The results are embodied in the following Table :—

Element.	Disk Drillings.	Ghost Chippings.
	Per cent.	Per cent.
Carbon . . .	0·19	0·27
Manganese . .	0·53	0·57
Silicon . . .	0·168	0·215
Sulphur . .	0·037	0·157, 0·117, 0·075; mean 0·12
Phosphorus . .	0·028	0·084, 0·101, 0·090, 0·054; mean 0·082
Chromium . .	0·75	0·74
Nickel . . .	3·74	4·24

From the foregoing Table it is obvious that the ghosts are compound and variable segregates, marked segregations of carbon, sulphur, phosphorus and nickel having taken place. In the Journal of the Iron and Steel Institute, No. 1, 1899, the Author and Dr. McWilliam published a Paper on "The Diffusion of Elements in Iron." They showed that at about 1,000° C. the

* See important note in Appendix (page 666).

elements of steel divided themselves into two groups, namely, migratory and non-migratory elements. The migratory group included the elements carbon, sulphur, phosphorus, and nickel. The above Table shows that the conclusions arrived at for a temperature of 1,000° C. also hold good for 1,500° C., at which temperature the steel is fluid. The chemical figures are somewhat astounding. It has been a generally accepted canon of metallurgical faith that ghosts, being higher in carbon, sulphur, and phosphorus than the main mass of the steel, necessarily froze last. The data presented in this research, however, prove conclusively that the ghosts freeze first at many degrees above the main mass freezing point. Protrusions of frozen ghosts, some of them 9 inches long with projections into the fluid mass of $\frac{3}{8}$ inch, are facts which cannot be disputed, although opposed to generally accepted theories. The behaviour of nickel would seem to be connected with a fact published before the Institution of Mechanical Engineers in March 1914 by the Author and Professor A. A. Read, that nickel, when present up to, say, 5 per cent., does not associate itself with the carbon, but forms a definite alloy with iron corresponding to the formula Fe_7Ni, and hence contains 13 per cent. nickel. This nickelide of iron has, as received from the rolls, a yield-point of nearly 60 tons per square inch, a maximum stress of nearly 90 tons per square inch, associated with an elongation on 2 inches of 11 per cent. and a reduction of area of 46 per cent. It is, therefore, perhaps the most remarkable metallic compound of iron.

Micrographic Analysis of the Frozen Ghosts and the Non-Segregated Steel in their Vicinity. Photomicrographs of 100 *diameters were taken and are reproduced, Figs.* 5 *and* 6, *Plate* 10, *at half scale, namely,* 50 *diameters.*—Fig. 5 is a transverse section of frozen ghosts which have protruded into the fluid metal for $\frac{3}{8}$ inch over a length of several inches, Fig. 7, Plate 11. The structure consists of dark-etching cells of chromiferous and manganiferous pearlite, surrounded by pale thick cell walls of ferrite containing dissolved phosphide of iron. Throughout the latter are circular areas and streaks of sulphide of manganese

the latter running like broken rivers down the middle of the cell walls.

Photomicrograph Fig. 6 is a transverse section of the steel in the vicinity of the frozen ghost. The dark-etching areas are chromiferous and manganiferous pearlite; the pale areas are ferrite crystals exhibiting very sparingly circles and streaks of sulphide of manganese. The structure, as was to be expected in so large and hence slowly cooled an ingot, is intensely crystalline.

The Formation of Ghosts.—In two Papers on "The Forms in which Sulphides may Exist in Steel Ingots," published respectively in the Journal of the Iron and Steel Institute, No. 1, 1914, and No. 1, 1915, the Author and Mr. G. R. Bolsover showed the existence of a definite solution or compound of iron and sulphide of manganese, which appeared to freeze before the main mass of the ingot, and on cooling broke up into a mixture of iron and dots of sulphide of manganese. The composition of this mixture was tentatively suggested as 88 per cent. Fe + 12 per cent. MnS. Such a composition would be obviously of a relatively low specific gravity and would tend to rise through the still unfrozen main mass of the steel. The Author suggests that as this definite substance rises in a thick pasty or semi-frozen state it forms in different parts of the ingot nuclei which gather to themselves the migratory compounds of steel, namely, carbide, phosphide, and in nickel steels, nickelide of iron. The Author also suggests that the extraordinarily gigantic ghosts present in each octagonal angle of the "bled" ingot described in this Paper were formed in the manner above enunciated.

Finally, the Author has cordially to thank Mr. G. R. Bolsover, Associate in Metallurgy of the University of Sheffield, for the great care with which he has ascertained the chemical compositions of the ghosts and the adjacent steel. Also Mr. J. H. Wreaks, B.Met., Lecturer on Metallography in the University of Sheffield, for the photomicrographs illustrating this Paper. He also respectfully tenders to The Right Hon. the Viscount Chetwynd his gratitude to

him for his great interest and invaluable help in one of the sections of this research.

The Paper is illustrated by Plates 10 and 11 and 3 Figs. in the letterpress, and is accompanied by an Appendix.

APPENDIX.

Since formulating the futtock shroud theory to explain the irregularly drawn-out nature of the ghosts in the cast ingot, the Author has made a further careful examination of the ghosts, and has come to the conclusion that the true explanation seems to be that after casting, at a position at the top of each ultimate "ghost line," was a segregate of roughly globular form as shown in the top photomicrograph of Fig. 1 (page 656). Then the rapid downward rush of many tons of molten steel when the break-out took place acted upon each pasty and more or less globular segregate in a manner similar to that of hammering or rolling, and drew them out into the elongated masses found grouped at each octagonal angle. The roughly globular rising masses of segregate all appear to have migrated into the angles, because the steel in those angles was at a higher temperature than the steel on the slightly radial sides of the octagon, the reason of this being that the solidified white-hot steel at the angles was thicker than that on the sides of the octagon, and hence more effectively lagged the fall of temperature at the angles, as compared with that taking place through the sides of the relatively cold mould.

Professor ARNOLD, before reading the Papers, said it was originally intended that his co-Author, Professor Read, should read the first Paper, and that he (Professor Arnold) should read the second. Unfortunately, however, Professor Read was quite unable to be present at the Meeting. He was not only a recruiting officer in Cardiff, but was also Organizer and Chief Inspector of Munitions. He had written stating that during the last year he had had only 48 hours' leave, and that it was quite impossible for him to get away to attend the Meeting, a fact which he (Professor Arnold) regretted very much.

Discussion in London.

The PRESIDENT said he had very great pleasure in proposing a cordial vote of thanks to the Authors for their extremely valuable Papers, which were somewhat out of his range of complete understanding.

The Resolution of thanks was carried with acclamation.

The PRESIDENT announced that, since the opening of the Meeting, he had received the following telegram from Sir Robert Hadfield: "Please tell the President, also Professor Arnold, how much I regret that, owing to being detained on urgent war work, it is not possible for me to be present at the reading of his two very interesting Papers, but I hope to send a contribution to the discussion."

Mr. L. PENDRED thought it would be generally admitted that the scientific value of Professor Arnold's and Professor Read's Paper was extremely high. It completed a brilliant series of researches which rounded off their knowledge of the four steels that had been investigated at Sheffield. But in the difficult times that lay almost immediately before Europe, it was the country which was best able to apply its scientific knowledge that would

(Mr. L. Pendred.)
succeed; and he therefore thought it would have been of great benefit to all the members if the Authors had stated whether molybdenum steel held out any prospects of being more useful in the arts than any of the other steels they had investigated. It was stated on pages 646–7 that molybdenum possessed high hardening properties. He would be very glad to know whether molybdenum was likely to be more useful in that direction than either vanadium or tungsten. It was possible also that the Authors in the course of their researches had discovered that molybdenum possessed other characteristics; it might, for example, make steel more resistive to corrosion, or be useful in some other directions than those with which the Authors had dealt. He felt sure it would be of benefit to all members of the Institution who were practical men, more interested in the use of steels than scientific metallurgy, if the Authors could give some slight hints in those directions.

Professor Robert H. Smith said the Authors had stated in their Paper that the practical difficulty of using molybdenum steel was its chemical instability, and that they were unable to explain the cause of that instability. He desired to ask them whether there was any hope of discovering that cause, and, if it were discovered, whether there would be any hope of remedying it.

Mr. E. R. Dolby asked the Authors whether a thin steel lamina, in which there were one or two "ghost lines," would be more readily inclined to fracture along the "ghost lines" than anywhere else.

Mr. Mark Robinson (Vice-President) said the President had challenged metallurgists to join in the discussion, but he could quite understand that, with such a champion as Professor Arnold at the lecture desk, very few metallurgists would care to criticize. Speaking as one who was not a metallurgist, and had no pretence to special knowledge upon that subject, he only wished to put on record the satisfaction he derived, as a person ignorant of, but, of course, interested in, such matters, from the lucid way in which

the Paper was written. It was extremely clear and of a most interesting nature, even to a man who had little technical knowledge of the subject, and he thought members might well put on record their appreciation of its form as well as of its substance.

The PRESIDENT said he was rather afraid that the legal darkness outside was invading the Meeting. The members did not generally fail at the Meetings of the Institution to tackle most of the subjects that were brought before them and to make the discussions interesting and lively. He supposed, however, on the present occasion it must be presumed that the Authors had dealt with a subject which was a little outside their practical studies, and that the unfortunate conditions of London after nine o'clock at night kept some of the members away from the Meeting who could have discussed it. Under the circumstances, he could only ask Professor Arnold to reply to the remarks that had been made.

Professor J. O. ARNOLD, in reply to the point raised by Mr. Pendred as to the future of molybdenum steel, said he did not think it was very promising. Molybdenum had had a very good chance, but a lot of trouble had been experienced with it owing to its curious unreliability as an element of steel. There was no doubt that it was at least twice as powerful as tungsten, but it was not nearly so reliable. If tungsten were properly used, the steel-maker knew exactly the result he would obtain, but that was not so with molybdenum, and he believed great losses and disasters had resulted from its too reckless use. It had therefore fallen very much into disuse. But, as was stated in the Paper, a small proportion of it to replace tungsten was very valuable indeed. The general verdict of tool-steel makers in regard to molybdenum steel was that, when a good molybdenum tool-steel was obtained, there was nothing to beat it, but one never knew when one was going to get a good one ; one might get four or five bad ones to a single good one. In his experience the unreliability of molybdenum, except in very small quantities, had led to its passing out of use very largely.

(Professor J. O. Arnold.)

Mr. Pendred had also raised the very important question of corrosion. One of his (Professor Arnold's) demonstrators, Mr. Leslie Aitchison, was taking the whole of the series of steels and making a complete set of corrosion tests on them. He had not yet received any results in regard to the molybdenum steels, so that he could not speak with regard to them, but so far as the tests had gone, the greatest uncorrosive element that had been discovered was chromium. The use of chromium in that respect was perfectly marvellous; in fact, a 15 per cent. chromium alloy mild steel was almost uncorrodible. Later on, the whole of the researches that had been made in regard to the various elements, both those he carried out for the Iron and Steel Institute and the four he had made for the Institution, would be published in a separate Paper, showing the exact influence of the elements on the corrosive properties of the bars. [Since reading the Paper, Mr. Aitchison had reported that molybdenum steel corroded very rapidly, the ferrite assuming the anode position, no doubt because the great chemical stability of the double carbide, Fe_3Mo_3C, rendered it strongly electro-negative to Fe.]

He did not quite follow the point Professor Smith raised in regard to the chemical instability. The difficulty experienced with steel was not so much the chemical instability as the thermal instability. The value of tool-steel was undoubtedly determined by the thermal stability of its hardenite. Many of the members had seen some of the new turning tool-steels containing tungsten, chromium, and vanadium running on a very hard bar with the edge of the nose of the tool at 700° C.—a nice red heat. He had run such tools, for experimental purposes, as long as eight or nine minutes on hard steel, running dry, of course. The main factor in that thermal stability was the tungsten hardenite. Iron hardenite broke down long before a red heat was obtained, namely, at 300° or 350° C., its thermal stability being so small. It was quite true, as Professor Smith had said, that the chemical and the thermal stabilities went pretty much together. The most unstable chemical was the iron carbide; one of the most stable was the tungsten carbide; and the most stable of all was the molybdenum double

carbide. The chief thing that should be aimed at in tool-steel was to get the greatest possible thermal stability—that is, the greatest possible working power, the highest speeds, the biggest cuts and the biggest traverse, and that was what steel-makers had been working at for such a long time. The foundation of that particular branch of the science was laid in 1857 by Robert Forrester Mushet.

Mr. Dolby had raised the very important point of the effect of stress on "ghost lines." In his experience, as he had stated in the Paper, with the "ghost lines" running longitudinally, if the stress were at right angles as in an alternating stress, the effect was practically nil. The Secretary had asked him a question in regard to the hardness of "ghost lines." They were really softer than the main portion of the steel, but they were all broken down by the streaks of sulphide of manganese, which constituted the mechanical weakness. The mechanical weakness was felt very little with a transverse stress, but he believed it was very dangerous with a longitudinal stress. For instance, where there was a longitudinal stress, as in the case of a gun, he would personally regard large "ghost lines" as a positive source of danger, but from a transverse stress he had no fear whatever.

Mr. PENDRED inquired what Professor Arnold meant by "transverse" and "longitudinal." Did he mean across and along the "ghost line"?

Professor ARNOLD said he meant a longitudinal stress. For instance, if there were "ghost lines" in a shaft, they would be under cross stress.

Mr. PENDRED said he understood Professor Arnold to mean where the "ghost lines" all ran parallel with the shaft.

Professor ARNOLD replied in the affirmative. In the Paper he had read before the Institution of Naval Architects, he gave a series of alternating tests at right angles to the "ghost lines" of sulphide of manganese, and parallel with them, and the value was only about

(Professor Arnold.)

half when the stress was parallel with the run of the "ghost lines."

Mr. E. R. Dolby said, supposing the lamina already mentioned were represented by a page of the Proceedings and there were a "ghost line" from top to bottom over the middle of the page, then if the page were bent transversely—as in turning it over—would the lamina break along the "ghost line"?

Professor Arnold said that would be so, due to the broken streaks of sulphide of manganese.

Captain H. Riall Sankey (Member of Council) presumed it would be just like the perforation of paper.

Professor Arnold agreed. In conclusion he desired to say that he was very much obliged to the gentlemen who had been good enough to take part in the discussion.

The President announced that the two Papers would be read again on Friday, 26th November, at Sheffield, when he believed the discussion would take a warmer tone than on the present occasion.

Discussion in Sheffield.

The CHAIRMAN (Mr. J. ROSSITER HOYLE, *Vice-President*), in calling upon Professor Arnold to read his two Papers, desired to say how very glad he was to see such a large gathering, and as a result he hoped a satisfactory and illuminating discussion would ensue. Although he was not present in London a week ago when the Papers were originally read, he had heard there was not a very lengthy or thorough discussion of the principal points concerned, largely, he thought, owing to the fact that a great many of the members who understood most about the subjects dealt with in the Papers were not present, and a very strong hope was then expressed that, when the Papers were read at Sheffield, they might be well criticized and considered from all points of view.

The CHAIRMAN, in proposing a most hearty vote of thanks to the Authors for their excellent Papers, which were of the deepest interest to all present, said that to some of the members the Papers were in parts beyond their ken, and personally he was afraid he must admit that he was a little out of his depth. He was glad, however, to see so many distinguished gentlemen present who could, with authority and with words that carried weight, discuss the Papers from every point of view.

The Resolution of Thanks was then put and carried with acclamation.

The CHAIRMAN, in calling upon Sir Robert Hadfield to open the discussion, said that Sheffield people did not very often see that gentleman at their Meetings. That, however, was not his fault, but was simply owing to the pressure of business which kept him in London. He knew that Sir Robert was always with them in his sympathies, especially in connexion with anything that promoted the scientific and manufacturing interest of the great city

(The Chairman.)

of Sheffield. He knew from the frequent occasions on which he met Sir Robert in London that he took the greatest interest in the Sheffield Societies, and it was extremely gratifying to him, as Chairman of the Meeting, to see Sir Robert present and to call upon him to open the discussion.

Sir Robert Hadfield (Member of Council) said that before he dealt with the interesting Papers that had been read, he desired to be allowed to make a few remarks on a subject which he was sure would evoke the very sincere sympathy of the members. He made the remarks because he happened to be the only official Member of the Council of the Iron and Steel Institute present at the Meeting. He was extremely sorry to inform the members that the Iron and Steel Institute had lost their worthy President, Dr. Greiner, who died on the previous day in Belgium. It was only about two and a half years since he (Sir Robert) had the pleasure of attending an Institute lunch in the beautiful courtyard of Dr. Greiner's château close to the Seraing Works, and on that occasion their late President treated them most royally. Whilst the Iron and Steel Institute had had an American President, it had not up to that time elected anyone from the Continent, and it was a great departure when a foreigner in the person of Dr. Greiner was elected to the position. The fact of appointing an eminent Continental gentleman as the President of the Iron and Steel Institute showed the cosmopolitan nature, not only of the Institute but of our great country of Great Britain. It showed that they wished to be in friendship with all the world. He was very sorry to say that the château near Seraing had been invaded by the Germans, and what had their terrible enemy done? Only a few months previously he had had the pleasure of seeing Dr. Greiner presented with what it was the aim of every metallurgist to win, namely, the Bessemer Gold Medal. When the Germans invaded the château the Gold Medal was stolen. The Iron and Steel Institute Council only a few months ago voted another Gold Medal to Dr. Greiner to replace the one that had been stolen. He suggested to the Chairman that he should put a resolution

of sympathy with the family of Dr. Greiner to the Meeting, and that, by rising, the Members should show their keen sense of the loss they had sustained.

The Chairman asked the members to rise, and in that manner express their sympathy with the family of Dr. Greiner, and the great loss that not only the Iron and Steel Institute had sustained, but also the iron and steel world at large, by his death.

The Resolution was carried in silence, all the members upstanding.

Sir Robert Hadfield (Member of Council), in opening the discussion, said he much regretted that owing to pressure of war work he was not able to be present at the reading of Professor Arnold's two very valuable Papers in London, but he was now in one way rather glad, because it had brought him that evening among many old friends, and had enabled him to see what excellent work this local Institution, of which he had many years ago been the first President, was continuing to do in Sheffield. He thought it was very creditable in a time of national stress like the present to see such a large audience present at a technical gathering to hear these two valuable Papers. Professor Arnold's Papers were particularly valuable, because they always had some useful bearing, founded as they were upon observations and research with practical aims and objects in view. That was an end which was often unfortunately not kept in mind. Even Professor Arnold's opponent admitted that his work was most thorough, and after knowing Professor Arnold personally for some twenty-five years, he could confirm that fact. He found, for example, that he was much more often referring to Professor Arnold's Papers than to those of any other Professor. Why? Because they had originally been based upon sound and correct work, which were not for a day, but for all time. He called the attention of some of their rising and younger men to the point that they should have this matter in view and try to get at the truth for truth's sake. After all, there was nothing more interesting, for, to use the old proverb, "Truth was stranger than

(Sir Robert Hadfield.)

fiction." Not long ago he was engaged with Professor Arnold in what might be described as some "military operations" relating to munitions, and found him staunch, firm and accurate under fire—that is, mental fire! It was not every Professor who could come out of such an ordeal and meet the foe of ignorance when suddenly engaged, not in discussing theoretical considerations, but facing with success the difficulties of practical facts and the difficulties of everyday work. He also referred to Professor Arnold's work because of the notice which recently appeared in one of the technical journals of America, the American *Iron Trade Review*, in which prominence was given to some unfair comments upon a Paper by Professor Arnold and Mr. Bolsover, entitled "How Sulphides may exist in Steel Ingots." It was stated that "The publication of this Paper, by Professor J. O. Arnold and G. R. Bolsover, seems rather surprising in a practical journal like the *Iron Trade Review*, because of the purely academic interest of the matter presented and the misleading nature of some of the statements. It is such articles as this that hinder the spread of confidence in the value of metallography among practical men, and give rise to the view that the microscope for the examination of metals is an interesting toy, of no practical use." He thought that a comment of this kind was most unfair in a journal of such standing, especially, too, when it was added that, "In the first place one wonders what kind of crucible steel they make in England if it contains four- or five-tenths of a per cent. of sulphur." It was difficult to imagine any sensible practical journal putting forward such reference, and this latter comment showed that they did not understand the importance of the Paper at all, which, of course, made no such absurd statement. This was therefore one of the reasons why he now specially referred at length to Professor Arnold's work. Whilst Professor Arnold required no word of praise on his part, the fact that such a large audience was present that evening showed what was thought of his work in Sheffield.

Referring now to the two Papers contributed, and first the one dealing with "Ghost Lines," he could not speak with much experience on the manufacture of heavy ingots such as those

referred to in this Paper. There was no doubt as to the tangible existence of "ghosts." This sounded an Irishism, seeing that ghosts one generally talked about were not supposed to exist, except in the imagination. It was satisfactory to find that Professor Arnold did not think the presence of ghosts of any vital importance, though in gun-steel their absence was probably more desirable than their presence, owing to the enormous scoring action of the hot gases from the explosives producing what was known as erosion, which quickly searched out even the slightest irregularity of structure or composition of the inner steel-tube. When it was borne in mind that, as Sir Andrew Noble had pointed out in his various Papers, not only had the inner tube to stand pressure to 25 tons per square inch or up to even higher, the gases produced reached enormous temperatures, 3,000° C. and over, he was sure therefore that members would agree it was most important that such tubes should represent Sheffield's very best possible product. The particular results described by Professor Arnold were most interesting, and it seemed to him that the Author accurately explained the origin of the curious results noticed in the very interesting large ingot referred to. As guns brought up the subject of war, he personally could not help thinking that after all, terrible as war was, it was teaching metallurgists a great deal, and that the information would benefit in many ways. It was producing many changes; English people were beginning to be a little more willing to try new ideas, and that was a good point. He could not help thinking that engineers would have soon to face the production of gun-steels which would withstand greater pressures and higher temperatures than had to be dealt with at the present time. Many of Professor Arnold's valuable Papers were in the direction of showing that it might be possible in the future to obtain different types of steels to those now existing, which might be of service to withstand much higher temperatures than those hitherto obtained.

He would also like to remind the members of a valuable Paper which seemed to him to bear upon the subject now dealt with read in 1905 before the Iron and Steel Institute by Captain H. G.

(Sir Robert Hadfield.)
Howorth, R.A., on "The Presence of Greenish Coloured Markings in the Fractured Surfaces of Test-Pieces." Captain Howorth was at that time in charge of the Government Inspection Offices in Surrey Street, Sheffield, and the Paper happened to be read during his Presidential year of office at the Iron and Steel Institute's famous Meeting in Sheffield in the autumn of 1905. Captain Howorth described in his Paper how certain forgings showed the presence of incipient flaws, which might under violent alternating stresses develop into cracks. He (Sir Robert) fully admitted that the type of imperfections described by Professor Arnold were not of that nature. Mr. Gledhill, General D. O'Callaghan, and General Sir John Wolfe Murray joined in the discussion, and also Dr. Stead by correspondence, whose remarks, being important, he would like to refresh the memory of the members by reading them. Dr. Stead stated that: "The presence of silicate of manganese in steel was what might naturally be expected, because of the well-known reaction between silicon, manganese, and oxide of iron, which was known to result in the formation of that compound. It was generally assumed that it floated to the top of the metal and escaped in the slag, but that it did not do so, and apparently did not actually separate until long after the mould had been filled with steel, was not known before Captain Howorth's interesting observation that the greater quantity of the substance was found at the lower instead of the upper part of the ingot, where one would naturally expect to find it. It would also lead to the belief that silicate of manganese was soluble in steel separated out coincidently with the solidification of the metal. The problem for metallurgists was how to avoid it." Even at the present day this important problem had not been altogether solved. It might be interesting to add that the greenish coloured markings referred to by Captain Howorth were found to contain 46 per cent. silica, 48 per cent. protoxide of manganese, and 4 per cent. alumina.

With regard to the Paper by Professor Arnold and Professor Read, Sir Robert Hadfield desired to add that some time ago he carried out some experiments, which he then intended to publish, but was unable to find time to do, with regard to the effect of

molybdenum upon iron. In many ways his results appeared to bear out those pointed out by the Authors in the present Paper. He made a series of steels, with the tests upon which he would not weary the members that evening, but would hand them to the Secretary, so that they would appear in the Journal of the Institution. The experiments dealt with the influence of varying percentages of molybdenum upon iron in the presence of very little carbon, and so far as he was aware, nothing of the kind had been previously published. His specimens ranged from those containing 0·24 per cent. molybdenum up to 23·75 per cent., and in none of them did the carbon exceed about 0·10 per cent. They therefore were able to see exactly what was the effect of the molybdenum present in the specimens. There was, too, practically no other element present; for example, the manganese did not exceed about 0·10 per cent. In the cast specimens the elastic limit seemed to rise very little by the increase of molybdenum. For example, the specimen with 0·10 per cent. carbon and 0·24 per cent. molybdenum showed an elastic limit of about 12 tons, a maximum stress of 23 tons, 35 per cent. elongation, about 58 per cent. reduction in area, and a ball-hardness number of 92. The specimen in the cast condition containing 3·0 per cent. molybdenum showed an increase to only about 18 tons elastic limit, which was not high, a tensile strength of about 30 tons; elongation went down to 15 per cent., and the ball-hardness increased to 130. Then, going up to 24 per cent. molybdenum, the breaking load was not high; there was practically no elongation. This is dealt with by him in a special note accompanying these remarks, headed "Alloys of Iron and Molybdenum" (page 701).

Dr. Thomas Swinden (Sheffield) thought that the Papers were of the greatest importance, both from the theoretical and practical standpoints. He wished to thank the Authors for the very appreciative tone in which the references had been made to his own work. The Authors referred only to one of his (Dr. Swinden's) Papers which was published in 1911, and to those interested in the subject he desired to point out that a sequel to it was published in the Carnegie Scholarship Memoirs of the Iron and Steel Institute for

(Dr. Thomas Swinden.)

1913, entitled "A Study of the Constitution of Carbon Molybdenum Steels." The latter Paper also had an Appendix on the mechanical properties of some low molybdenum alloy steels, which he thought was of some interest from a practical standpoint.

Referring to the mechanical properties, his own figures bore out very largely those dealt with in the Paper, and also the interesting figures which Sir Robert Hadfield had contributed to the discussion. None of his (the speaker's) steels were so low in carbon, but he wished to point out that, even in steels containing an appreciable amount of carbon, similar conclusions might be arrived at. For example, two steels, both containing 0·44 per cent. of carbon, and respectively 1·05 and 8·11 per cent. molybdenum, in the annealed state gave almost identical tests. The yield-point was 18·36 in one case and 17·25 in the other. In the normal state the yield-point was 37·81 in the first and 38·16 in the second. Curiously enough, in the rolled condition the influence of molybdenum was very marked. The yield-point in the rolled condition was 34·40 tons with 1 per cent. molybdenum, and 68·80 tons with 8 per cent., whilst the breaking loads were 54·40 tons and 96·0 tons respectively. The Authors stated on page 647: "It is therefore clear that so powerful a steel-producing element should be used sparingly, avoiding high percentages. With low percentages it undoubtedly exerts a beneficial influence on certain classes of steel." The inference he presumed was there made that, with fairly high percentages, bad results must necessarily be obtained. That, he thought, was rather overstating the case, because with 8 per cent. molybdenum it was possible to get very good mechanical properties, although, of course, not of commercial value, because the cost of the molybdenum would be too high, and the same tests could be obtained in a very much cheaper manner.

Leaving the mechanical properties, the point in the Paper of chief interest to him dealt with the analyses of the carbides. Those who had read both Papers knew there was a difference of opinion in the interpretation of the results. He was extremely delighted to see that from the chemical standpoint good agreement occurred. In passing, he might say that in the case of the steel,

which gave 3·60 per cent. carbon in the carbide residue, the result could not have been very low, because 94·1 per cent. of the carbon in the steel was recovered in the carbide; so that if the whole of the carbon had been recovered, the figure would have been only 3·82. This might, however, be regarded as a detail.

Dealing with the question of carbides, one very important point which had been referred to in several of the Authors' Papers was the presence of free carbon in the carbide residue. Speaking entirely as a student searching for knowledge, he desired to ask Professor Arnold if there was any proof of Fe_3C being decomposed electrolytically by interaction with another carbide or double carbide under the conditions of separation. That was a point which, to his mind, was of the greatest interest, because if such action took place, it was very important to know to what extent it did so, as the effect was quite a governing factor in the ultimate analysis. The Authors had described Fe_3Mo_3C as a remarkable compound, and he thought it must be recognized as such, because it was taken as an axiom that carbon steel contained Fe_3C, and that particular compound was Fe_3C with three molecules of molybdenum combined. That, from a purely chemical standpoint, was a very remarkable thing. Again, as a student he would very much like to hear Professor Arnold's opinion as to what valency might be attributed to the various elements, and how such a compound could exist in a stable form. As illustrating the stability of that compound, it was mentioned in the Paper (page 637) that it was insoluble in strong boiling hydrochloric acid. But that in itself, as Professor Arnold no doubt knew full well, was no absolute proof, since metallic molybdenum was not soluble to any appreciable extent in strong boiling hydrochloric acid if it was not oxidized. It therefore raised the important point: Was it possible that instead of being the compound Fe_3Mo_3C, the residue might consist of Fe_3C and metallic molybdenum? That might sound a very far-fetched suggestion, in view of the thorough research which the Authors had carried out, but it was one which he thought was worth considering. For the benefit of those members who were not conversant with the analysis, he wished to explain it was

(Dr. Thomas Swinden.)
obvious that if there were, say, 6 molecules of Fe_3C and 1 molecule of Fe_3Mo_3C, the chemical results of the carbide analysis would be equally well explained by assuming 7 molecules of Fe_3C and 3 molecules of molybdenum to exist in the residue.

With regard to the recalescence data, they would be awaited with the greatest interest, because they had to be explained on the results of the carbide analysis. A very great advance would no doubt have been made when those curves were completed and the explanations were forthcoming. If he might add one more doubt, if he might put it in that way, he would like to draw attention to the extensive series of curves, something like 200 in number, of molybdenum steels, which were published in 1913. Taking, for example, a steel containing 0·87 per cent. of carbon and 1 per cent. of molybdenum which, according to the Authors' analyses, would contain in the carbide, say, 80 per cent. of Fe_3C and 20 per cent. Fe_3Mo_3C. If cooled from about 800° C., the steel gave a normal point corresponding to $Ar_{1\cdot 2\cdot 3}$. at about 710° C. If heated to 880° C., no point occurred at the normal temperature—that was an absolute fact—but a point occurred at about 580° C., which was almost equal in magnitude. The temperature at which that change-point was going to occur on cooling could be controlled by the temperature to which the steel was heated between 800° and 900° C. If the steel were heated to 880° C., according to the conclusions in the Paper the change from carbon molybdenum pearlite into carbon molybdenum hardenite had not begun to take place; that began at about 900° C. What, then, was the change which took place at 580° C.? What was the change which took place at 710° C. when cooled from 800° C. originally? If cooled from 880° C., 80 per cent. of Fe_3C was present. Why was not the normal $Ar_{1\cdot 2\cdot 3}$. found? It was not found. That, no doubt, Professor Arnold had already proved for himself; and since no ferro-carbon hardenite had been formed, it would be very interesting to know exactly what was the reaction taking place at the low temperature. Those points had occurred to him, as the members would no doubt recognize, as one who had studied the subject deeply, and he hoped Professor Arnold would not take what he had

said, as he did in regard to his contribution on the Tungsten Paper, as savouring of hypercriticism. It was not that for one moment. He was a student anxious to learn and hear all the facts which had been proved, and which would be proved by further work, but personally he must say he could not see an explanation of the recalescence data on the isolation of the double carbide Fe_3Mo_3C.

Commander H. G. Jackson, R.N., said he felt it was rather brave of him to stand up before a body of experts to deal with a technical subject, particularly in face of Professor Arnold's warning that they must be careful what they said. There were, however, several points in the Paper of particular interest to the Admiralty Ordnance Inspectors. They were greatly troubled with "ghosts" in large gun-forgings, and regarded them with grave suspicion. They did not wish to reject a valuable bit of steel on suspicion only, and yet they did not like to pass into the Service material with which they were not entirely satisfied. The strain on gun-forgings was fairly considerable; it was a shock test, and they really did not know what happened to the forgings when the guns were fired. They did know that there was a very large reserve of strength in the guns when they were first built up, but in the present war a large number of cases had occurred, as had been anticipated, of guns being struck by portions of shells from the enemy, which had damaged their exterior to a certain extent without affecting the bore, and the guns had gone on firing with, of course, part of their reserve of strength gone.

Professor Arnold had dealt with the importance of "ghost lines" from the point of view of propeller-shafts, but personally he would be very glad if the Author would state what his opinion was of their importance in regard to gun-forgings. One or two points in connexion with "ghost lines" had come under his observation which were not dealt with in the Paper. One was that when a "ghost line" appeared in a forging, it generally extended practically over its whole length and not over a portion of the forging; so presumably it existed originally on the whole length of the

(Commander H. G. Jackson, R.N.)

original ingot. The "ghost lines" also appeared more on the outside than on the inside of the forgings. For the purpose of examining the larger forgings for guns of 13·5 inches and over, an inspector passed right through the inner tube, and, of course, the outer tubes could be examined carefully, but it was possible that the comparative absence of "ghost lines" on the inside was not a real absence, but was only due to the difficulty of carrying out the examination, because, as the members would readily appreciate, it was very much easier to examine the outside than the inside of a tube. Professor Arnold had mentioned that in the ingot which bled there were several "ghosts" hanging on round its top portion, but he had not mentioned why he identified those particular excrescences as being connected with the actual "ghosts" which subsequently appeared in the forgings.

He noticed that the analysis obtained from them did not compare very favourably with the difference between the analysis of shavings from portions of forgings showing "ghosts," and the analysis of ghost-free portions of the forging. The statement was made: "The foregoing figures show that the inclusion in the steel shavings of some 'ghost lines' had raised the carbon 19, the silicon 287, the manganese 35, the sulphur 125, and the phosphorus 44 per cent., the ghost-free figures being taken as 100 per cent." Looking at that, one would expect to find a large proportion of silicon in the analysis of the chippings from the excrescences if they were the true cause of the "ghosts," but instead of that the silicon had really increased over that found in the disk drillings by less than either the sulphur or the phosphorus. He hoped that Professor Arnold would kindly deal with that question.

Mr. E. H. Saniter (Sheffield) said the Paper on molybdenum added another research to the very useful and valuable researches that Professor Arnold and Professor Read had previously carried out. He did not propose to deal with the question of molybdenum carbides, because he had not studied the subject, but he desiréd to make a few remarks on the Paper on "Ghost Lines." "Ghosts" were exceedingly important and sometimes annoying things to

come across. The difficulty of knowing why they occurred in one ingot and did not occur in another had not been explained. He quite agreed with Professor Arnold's remarks with reference to "ghosts" in a propeller-shaft; he did not see how "longitudinal" ghosts could have any material detrimental effect in such an article. With reference to Commander Jackson's remarks on the subject of guns, Professor Arnold might give him more comfort, but the only comfort he could give him in regard to "ghosts" was that if they were long they were not very deep, and the wall of the gun was so much thicker that there was a good deal of steel behind.

With regard to the formation of "ghosts," he owned at once that some of the theories put forward by the Author were not those which he had believed to be correct for a very long time, and which, even in spite of Professor Arnold's persuasion, he was not at the present moment quite prepared to accept. The question of the freezing out of sulphide of manganese from the substance which was supposed to exist in the steel containing 88 per cent. of iron and 12 per cent. of sulphide of manganese presented one difficulty, that the manganese was not found to segregate in proportion to the segregation of sulphur in the steel. Professor Howe's explanation of the formation of "ghosts" on the "land-locked bay theory," the last and most fusible portion being the centre of the land-locked bay, commended itself much more to him. Consequently he could not accept at the present moment—although he did not wish to make the assertion dogmatically—that the "ghosts" found by Professor Arnold had frozen out ahead of the purer steel which flowed away. He presumed that the "ghosts" were found on a portion of the ingot which was in the chill and not in the brick head.

Professor Arnold replied in the affirmative.

Mr. Saniter said that in the angle of the octagon a freezing was set up in two directions. As far as he could make out, the "land-locked bay ghosts," as they were called by Professor Howe, were the same as the "futtock shroud ghosts," as they were called by Professor Arnold, although probably the futtock shroud was

(Mr. Saniter.)

more in a vertical than a horizontal direction. Personally, he (Mr. Saniter) found "ghosts" some years ago in the angles of octagon ingots, quite close in the angle. Professor Arnold had apparently abandoned what he called the "futtock shroud theory," but he (Mr. Saniter) thought the word "shroud" could still be retained if they used it in the different sense of a shroud containing a corpse. He suggested that the corpse in the present case was the segregation which Professor Arnold discovered, and that it was surrounded at the time the ingot broke out by a solid shroud of the purer metal which prevented it running away, although it (the corpse) was still in a fusible state. He wished he had had an opportunity of seeing the specimens before the Meeting. He merely threw it out as a suggestion to get over the difficulty of having to believe that carbide of iron and phosphide of iron—he left the sulphur out for the moment—would become solid before the general mass of the steel.

Professor J. O. Arnold, in reply, said he was extremely pleased at the criticisms which had been offered on the Papers. They had been made in such a nice spirit that neither party cared which was right, as long as they arrived at the truth. The information given by Sir Robert Hadfield was very valuable. One of the Authors' Papers might be called "The Influence of Molybdenum on Annealed Steel"; Sir Robert's very interesting comparison might be called "The Influence of Molybdenum on practically Pure Iron"; and it would form a most valuable supplementary Paper in the annals of the Institution.

He listened with very great interest to Dr. Swinden's criticism. He hoped that Dr. Swinden did not think for a moment that he doubted his recalescence results; in fact, he had no doubt that the Authors would confirm them. The only point of difference was that the Authors preferred to base their interpretation on the actually isolated carbides rather than on a theoretical interpretation of recalescence curves, but he had not the slightest doubt that, when the Authors had dealt fully with the recalescence work, they would find an explanation which would sweep away the differences of opinion between Dr. Swinden and themselves.

There was one point, however, he thought Dr. Swinden had overlooked; he asked for evidence of the liberation of carbon by another carbide or another constituent of different potential. Such an example was given in a Paper to which he would now very briefly refer. It was obtained many years ago, and published before The Institution of Civil Engineers in 1895. Professor Read and he electrolyzed a 0·9 per cent. carbon normalized steel, and they got out about 96 per cent. of the total carbon as Fe_3C. Then they electrolyzed a normalized steel with 1·47 carbon, and got out an amount of carbide equivalent to only about 0·6 per cent. of carbon, the reason being that the excess carbon over 0·9 existed as cementite, which was electro-negative to the cementite of pearlite. Consequently that meant that what they obtained was really the carbon of supersaturation, and a flocculent mass of carbon from the cementite of the pearlite from which the iron had disappeared. This worked out almost to theory. That was a very clear example such as Dr. Swinden very properly asked for.

He quite agreed with Dr. Swinden's remarks about the hydrochloric acid insolubility being no proof so far as molybdenum was concerned, but he asked the members to remember that the compound was absolutely non-magnetic so far as a powerful magnet was concerned. If, as Dr. Swinden suggested, they had a mixture of a carbide of iron and free molybdenum, it was quite certain that every bit of that carbide of iron would have been violently attracted by the magnet, but they found it was not so at all. If, as Dr. Swinden suggested, free metallic molybdenum were present, when the combustion was done in oxygen molybdenum would be volatilized as oxide of molybdenum, but they did not get the smallest sublimation throughout the whole of the combustions. The Authors would go very carefully and fully, bit by bit, through the whole of Dr. Swinden's recalescence data, and personally he had not the slightest doubt in his own mind that it would be found they were absolutely at one so far as practical observation went. The time would then come when both points of view could be reviewed together, and he felt sure they would come to an agreement. He would deal more fully in writing with the other points raised by Dr. Swinden.

(Professor J. O. Arnold.)

With reference to the remarks made by Commander Jackson as to the difference between a longitudinal stress on a "ghost" and a cross stress, he quite agreed with him that in a gun, where the stress was more or less longitudinal, large "ghosts," at any rate, would undoubtedly be a source of weakness; but he also reminded Commander Jackson that, whatever the effect might be, such steel could not be obtained without "ghosts." Those huge "ghosts," exhibited in the vestibule, which he hoped would not alarm Commander Jackson, were in the portion that was cut away to scrap, so that he never need be afraid of meeting giants like those in his gun-tubes. With reference to the comparison between the analyses, he thought if Commander Jackson would carefully look at the figures again, he would find that the Authors explicitly pointed out that the last "ghosts" did not contain mixed silicate, and that the difference in analysis was entirely due, accidentally or incidentally, to silicate of manganese. As was stated in the Paper, the first set of shavings was contaminated with the pure steel; they could not get the "ghosts" altogether out, but the "ghosts" to which he now referred Commander Jackson were the genuine article; they had been chipped off.

With regard to Mr. Saniter's criticism, he advised that gentleman to wait until after he had seen the specimens before he made up his mind. He did not think he had quite realized their importance. Mr. Saniter would see the stumps from which the "ghosts" were amputated, and which were protruding $\frac{1}{4}$ inch to $\frac{1}{2}$ inch into the liquid mass, and he would see, in the micrographs above, the curious alloy or eutectic, or whatever he liked to call it, which he (Professor Arnold) suggested corresponded to 88 per cent. of iron and 12 per cent. of MnS. It looked almost exactly like well-annealed pearlite. In the original drawings, which were extremely carefully made by his colleague, Mr. Bolsover, two colours would be seen, in which, if they substituted white carbide of iron, instead of the dove-grey sulphide of manganese, they might be little balls of Fe_3C such as were obtained on annealing. If Mr. Saniter cared to go through them, the Authors had a very large collection of carefully-made sulphide ingots of known history, and he thought

when Mr. Saniter had examined them as many times as they had, he would be inclined to alter his opinion. At the same time, he was extremely obliged to him for his criticism. He had presented another point of view, and it was only by comparing opposite points of view that the truth was eventually arrived at.

The CHAIRMAN, in proposing a vote of thanks to the University of Sheffield for the use of the Mappin Hall, said that the Secretary, Mr. Worthington, who had come down specially to attend the Meeting, was very anxious that those of the members who could should contribute to the discussion in writing, so as to make the Papers of additional interest. Personally he had intended to tell a few "ghost" stories himself, because Professor Arnold was quite unaware that he (the Chairman) began the research into "ghosts" more than thirty-three years ago, and at the time satisfied himself that they were not detrimental in guns. He hoped Commander Jackson would kindly note that that was the opinion of Captain Noble, as he then was, later Sir Andrew Noble, who was now unfortunately deceased.

The resolution of thanks was carried with acclamation.

Communications.

Dr. W. H. HATFIELD (Sheffield) wrote that he had been much interested in the molybdenum steel research. They were much indebted to the Authors for the further instalment of this series of researches upon the constitution of alloy steels. Their method of attacking the question of the "physical and mechanical relationship" existing between the iron, carbon, and other elements in steels was one which in their hands had resulted in the bringing forward of much new data likely to be of great use to metallurgists. This series of researches was now much appreciated both at home

(Dr. W. H. Hatfield.)

and abroad, and it was to be hoped that the present publication would not be the last. Methods of the type used in the research for isolating the carbides were open to certain criticisms, but in the light of his own (the writer's) experience of them, he considered that better methods had not yet been advanced.

From a theoretical point of view, perhaps the most important fact brought out in the Paper was the existence of the apparently stable compound, Fe_3Mo_3C. The Authors appeared to have been at much trouble to determine this to be a compound and not a mechanical mixture of carbide and molybdenum. The data as to the non-magnetic character of this residue were certainly strong evidence in favour of their point of view, as was also the fact that the same compound was extracted from the hardened steel. In considering this question, however, the valency of the elements concerned must be taken into consideration along with the balancing of the affinities of the atoms within the molecule, and these factors in the case of ternary compounds brought one face to face with various extremely complicated problems. For instance, accepting, as one might on the Authors' evidence, that the compound did exist, it still might be questioned whether it was a simple double carbide, and he (Dr. Hatfield) would like the Authors to expound further this phase of the matter. The valency of an element might vary according to the element with which it combined, and much more had still to be learned in regard to carbon and iron in this respect.

Further, it was usual at present to accept the carbide Fe_3C as being the only carbide phase in the iron-carbide system, but if Fe_3Mo_3C existed, was it not logical to ask whether the molybdenum in the new compound might under certain conditions be replaced by iron, thus producing a lower carbide, say Fe_6C? Such a carbide Fe_6C might not be as stable in the lower reaches of temperature as the Fe_3Mo_3C, and hence the confirmation of the discovery of this new compound might give an entirely fresh trend to our thoughts on the relationship existing between the iron and carbon in steels. At the same time, it must not be overlooked that it was possible that the relative valency of iron and molybdenum in

relation to carbon might not be identical. The whole subject was intensely interesting, and was worth very careful consideration. The practical importance of a number of the points brought forward in the Paper was obvious, and it was to be hoped that they would be thoroughly discussed. The writer could not but largely share the Authors' views as to the attempted explanations of the inherent hardness of the various solid solutions met with in the different steels, and much as he (Dr. Hatfield) had laboured to follow the ingenious theories from time to time advanced in explanation, he felt that we were really about as far from a satisfactory solution in this case as we were in attempting to explain the difference in hardness between quartz and the diamond.

Turning to the Paper on "Ghost Lines," he would like to congratulate Professor Arnold upon an extremely interesting Paper. There were, however, one or two questions he would like to ask. In the first place, the Author considered it probable that a "carburized" ghost might by annealing be converted into a decarburized one. Had Professor Arnold actually accomplished this transformation experimentally? To the writer it did not seem to be a sufficiently established possibility. The assumption was that the higher phosphide in the ghost (say 0·10 per cent.) was responsible during heat-treatment for ejecting the carbide, and yet he (Dr. Hatfield) considered he demonstrated in his Paper before the Iron and Steel Institute last autumn that in a saturated solid solution of carbide in iron, in the presence of an excess carbon, as much as 0·20 per cent. of phosphorus might be retained in solution. This view of the matter should be taken into consideration during a discussion upon the origin of "ghosts."

Professor Arnold was to be congratulated upon securing such an excellent specimen as the one which was the central feature of his Paper. His explanation of the occurrence of the "ghost lines" was most ingenious, but obviously depended entirely upon the Author's contention that the segregate had a higher freezing-point than the remainder of the material. The only other explanation, in the writer's opinion, would be that based upon the current understanding to the effect that the segregate had a lower freezing-

(Dr. W. H. Hatfield.)
point than the mass, in which case it might be considered that the "ghosts" represented the last portions to freeze which had drained through the already practically frozen wall of steel. A careful scrutiny of the interior of the piece above the "ghosts" might give additional useful data on the subject.

Mr. THOMAS F. RUSSELL (Sheffield) sent the following notes, which he thought might be a slight improvement on the interpretation of the experimental results shown in the Paper on Carbides of Molybdenum.

STEEL NO. 1530A. C 0·75, Mo 4·95

100 grammes of this steel contains :—

				C_{12}	Fe_{168}	Mo_{288}
	8·043 grammes	Fe_3Mo_3C	=	0·206	2·887	4·95
and	8·16 ,,	Fe_3C	=	0·544	7·616	—
	16·20			0·75	10·503	4·95
		Per cent.		4·63	64·81	30·56

Hence the theoretical composition of the carbides is: $2 \cdot 638\ Fe_3C + Fe_3Mo_3C$, corresponding to 4·63 per cent. C, 64·81 Fe, 30·56 Mo. Experiment showed that 7·3690 grammes of steel gave 0·8653 gramme of mixed carbides, or only 11·743 per cent., against the theoretical 16·20—that is, 4·457 grammes pass into solution (or gas).

Again, experiment showed that only 78·16 per cent. of the available Mo was recovered. There was proof in the Paper that when Fe_3Mo_3C was decomposed, the Fe, Mo and C disappeared, and with Fe_3C, C was deposited. Therefore 100 grammes of the steel gave $\frac{78 \cdot 16}{100} \times 8 \cdot 043\ Fe_3Mo_3C = 6 \cdot 2864$ grammes—that is, 1·757 gramme of ferro-molybdenum carbide was decomposed, and 2·700 grammes of Fe (originally as Fe_3C) were lost, making a total loss of 4·457 grammes.

So that, starting with the two results, (1) percentage recovery of carbides, and (2) percentage recovery of Mo, and assuming that

both Fe_3Mo_3C and Fe_3C were decomposed, the theoretical composition of the deposit was

	C	Fe	Mo
6·286 parts of Fe_3Mo_3C	0·161	2·253	3·872
5·278 ,, ,, Fe_3C	0·352	4·926	—
0·192 ,, ,, C	0·192	—	—
	0·705	7·179	3·872
Per cent.	5·99	61·07	32·93
A remarkable agreement with the Analysis	5·42	61·54	32·96

(See note at the end on the molybdenum result.)

The carbon result is well within the experimental limit of error.

Steel No. 1529a with C 0·71, Mo 10·15.

The results of this steel have been worked out in exactly the same way:—

	C	Fe	Mo
The *theoretical* composition of the deposit is .	3·81	42·43	53·7
The actual Analysis is	3·67	42·08	53·71

The agreement between these results was very marked. It seemed to the writer that when there was a loss of molybdenum amounting to as much as 22 per cent., one could not interpret the results without taking some note of this loss. Did this do so in a satisfactory manner, and was it not a good proof that *both* ferro-molybdenum carbide and cementite were decomposed?

Note on the Molybdenum Result.—The molybdenum figure, as given in the theoretical analysis, was not strictly theoretical, as this was obtained from the percentage recovery of molybdenum, and this in turn from the actual Mo analysis of the deposit.

The carbon and iron results were, however, *strictly theoretical*, and the close agreement with the actual analysis called for attention.

Mr. G. O. B. Willis wrote that he would like to ask if Professor Arnold had formed an opinion as to what were the conditions which determined whether a large ingot should develop "ghosts" or not

(Mr. G. O. B. Willis.)

One found that a forging made from a certain ingot showed decided "ghost lines," whereas others cast in the same chill, of very similar analysis and made from the same irons, etc., were apparently quite free from "ghosts." It could therefore be assumed that there was some condition, or set of conditions, which influenced the result one way or the other, and a knowledge of this would be very helpful to steelmakers to enable them to avoid these "ghosts." Professor Arnold's theory of the formation of the "ghosts," or the segregations which developed into "ghosts," seemed to upset the hitherto generally accepted theory of their formation, namely, that the compound of iron and manganese sulphide, which gathered to itself carbon, phosphorus, sulphur, etc., and lodged in the corners where the heat was greater (owing to the greater thickness of metal), had a lower freezing-point than the main mass, and was trapped in these positions on the main mass solidifying. Professor Arnold in his present Paper said that this manganese sulphide froze out *first*, and in the case of the large ingot which burst, quoted the protruding streaks of segregates as confirming this. Might not these streaks have been formed by globules of segregates being squeezed out from between the main mass crystals *before they had solidified*, by the contraction of the main mass, and then run down and frozen? The writer would be interested to learn the views of other metallurgical experts on this point.

The AUTHORS, in further reply to Dr. Swinden, might remark that in the residues from steels 1531A and 1530A, which were high in Fe_3C, some iron was dissolved on boiling the residual carbides in hydrochloric acid and a little free carbon liberated from the evolved hydrocarbons. With reference to Dr. Swinden's steel No. 16, the Authors found it to contain, not 3·6, but 4·1 per cent. of carbon, and of this amount 94·5 per cent. was found in the residue. Dr. Swinden suggested that the Authors' Fe_3Mo_3C might consist of about 62 per cent. of metallic molybdenum and 38 per cent. of Fe_3C. Surely in such a mixture the Fe_3C could be removed by the magnet and would dissolve in hot hydrochloric acid solution with evolution of hydrocarbons and separation of considerable free

carbon! The Authors fully recognized the value of the point raised by Dr. Swinden as to the valencies involved in a compound so remarkable and unexpected as ferro-molybdenum carbide, and later on it would be dealt with, since the point had also been ably raised by Dr. Hatfield.

In further reply to Mr. Saniter as well as to the interesting suggestions of Mr. G. O. B. Willis in the correspondence, Professor Arnold could not see how a heavy downward rush of tons of molten steel less fusible than "ghosts," according to Professor Howe's theory, could leave solid ribs of segregates more fusible than the main mass of steel. Would there not be, instead of protruding ribs of segregate, *hollows from which the more fusible segregates had run out with the main mass* of the "bleeding" steel? Whilst thanking Mr. Saniter and Mr. Willis for their remarks on this matter, the Author was quite unable to visualize mentally the explanations they had suggested in so non-dogmatic a manner. At the same time, the Author was most anxious to investigate further the surprising phenomena observed, and would be much obliged to both gentlemen if they could in any way help him to obtain more data.

In reply to Dr. Hatfield, the Author had never actually transformed a black "ghost" to a white one, the first named being difficult to get hold of in masses sufficient for experiment. Nevertheless, he was strongly inclined to believe in such transformations in the case of structural steels. This might be so without in any way throwing doubt on the interesting experiments made by Dr. Hatfield on hard steels. In reply to Dr. Hatfield's quite legitimate criticism on valency, it might be stated that the Authors had included a reference to this in the first draft of their Paper, but struck it out as being perhaps of too abstract a chemical nature. However, as the matter had been raised both by Drs. Swinden and Hatfield, one of the Authors requested his colleague, Mr. F. C. Thompson, M.Met., B.Sc., kindly to prepare for them a brief report on this question. Mr. Thompson's interesting and thoughtful remarks (for which the Authors sincerely thanked him) were as follows:—

(The Authors.)

Ferro-Molybdenum Carbide from the Valency point of view.—The remarkably interesting discovery of a double carbide of iron and molybdenum by Professors Arnold and Read raised the question as to how far the formula for such a compound might be in accord with the ordinary valency assumptions. The difficulty of explaining the formulæ for many inter-metallic compounds, if the elements retained their usual valencies, had always been great, and in many respects metallic carbides showed a remarkable similarity to such compounds. The point was well illustrated by the substances whose formulæ are $NaHg_2$, $AuSn_4$, Au_3Zn_5, and even Fe_3C.

Much of the rigidity associated with the older views of valency had been lost in recent years as new compounds have come to light, and especially in view of Thelés' hypothesis of "residual" or "partial" valencies. The variability of the valency of an element in its different compounds was often very marked, the combining power being frequently a function of the temperature. In the case of molybdenum this variation was specially noteworthy, and the older conceptions that, in cases where a variation of valency was found, the combining power was always odd or always even was completely contradicted.

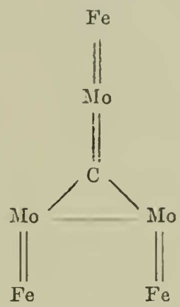
The highest chloride yet prepared had the formula $MoCl_5$. This, however, readily lost chlorine, becoming the tetra-chloride $MoCl_4$. In addition, the di- and tri-chlorides $MoCl_2$ and $MoCl_3$ were also known. Although the hexa-chloride $MoCl_6$ was not known, the corresponding fluorine compound MoF_6 was, being prepared by the action of fluorine on finely divided molybdenum at a temperature of 60° to 70° C. The existence of oxyfluorides and oxychlorides corresponding to MoO_3 was well established, and other oxides having the formulæ Mo_2O_3 and MoO_2 was also known. The valency of molybdenum might, therefore, be anything from two to six, but it was of interest that according to Ostwald the most stable compounds were those of the hexavalent type.

The construction of a constitutional formula for the carbide Fe_3Mo_3C was therefore facilitated in one direction, though corresponding uncertainties were introduced in others. In any

formula the valency of the carbon must undoubtedly be four while the iron was probably in the ferrous (divalent) state.

Fig. 8 gave a possible and indeed theoretically stable structure of this carbide with molybdenum in the tetravalent state:—

FIG. 8.



It was quite conceivable, however, that the molecule of the double carbide was $Fe_6Mo_6C_2$ rather than the simple Fe_3Mo_3C, the real molecular weights of such carbides as exist in steels having never yet been determined. Figs. 9, 10, 11, and 12 showed possible structures in this case if the valency of molybdenum were 3, 4, 5, and 6 respectively:—

FIG. 9.

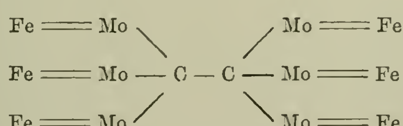
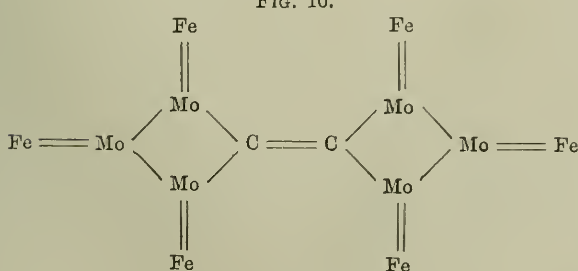


FIG. 10.



(The Authors.)

Fig. 11.

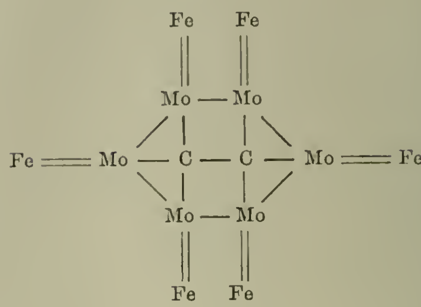
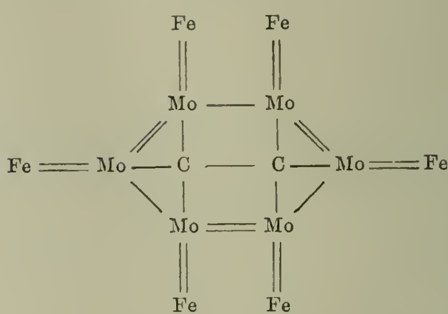


Fig. 12.



Formulæ 3 and 4 were worthy of further brief consideration. The remarkable chemical stability of benzine C_6H_6 was associated with the six-membered carbon ring which was the essential basis of its structure. Figs. 11 and 12 illustrated the structure of a carbide containing a six-membered ring of molybdenum, and it was specially noteworthy, therefore, that this carbide stood alone among those found in plain carbon and alloy steels in its resistance to chemical attack. Such structures were, to some extent, mere juggling with symbols and linkages, since the chemical reactions of the compound were unknown. They possessed, however, the real value in the present instance of showing that the discovery of the Authors was in quite satisfactory accord with the requirements of general chemistry.

The Authors had read with very great interest the criticism of Mr. T. F. Russell (Associate in Metallurgy in the University of Sheffield) interpreting in another (and indeed an improved) way the analytical results obtained from steels Nos. 1530A and 1529A. With Mr. Russell's views the Authors were in substantial agreement, and sincerely thanked him for his ably worked out confirmatory calculations.

ADDENDUM ON ALLOYS OF IRON AND MOLYBDENUM.

By Sir ROBERT A. HADFIELD, D.Sc., D.Met., F.R.S.,
Member of Council.

With reference to the effect of molybdenum upon iron, about eight years ago he (Sir Robert Hadfield) made a very complete series of tests, of which the following are the particulars. As this was the first time such a complete series of these Molybdenum-Iron alloys containing so few variants has been prepared, and hitherto not made public, he has much pleasure in presenting the particulars of the research to the Institution.

(*a*) (Table 12). Series 1848, in which the molybdenum was added by means of ferro-molybdenum. The results of these various tests are shown on the accompanying diagram, Fig. 13 (pages 702–703).

(*b*) (Table 13). Series 1921, in which the molybdenum was added in the metallic form. The results of these various tests are shown on the accompanying diagram, Fig. 14 (pages 702–703).

Series 1921, made with the metallic molybdenum, shows by far the most uniform results, therefore in these remarks reference will be made more particularly to this series. The curves on diagram Fig. 14, representing Series 1921, indicate in a very clear manner the changes brought about by the gradually increasing percentage of molybdenum, varying from 0·24 per cent. to no less than 23·75 per cent.

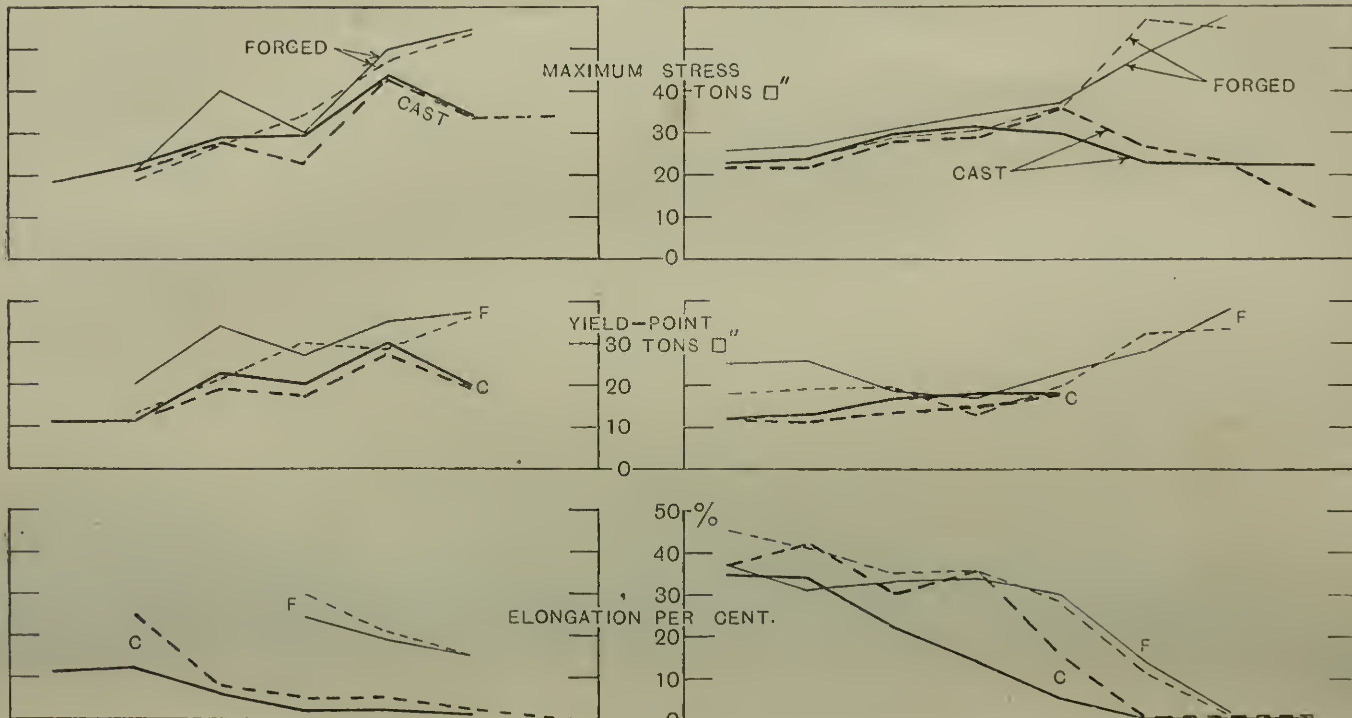
In both series, Nos. 1848 and 1921, the carbon, the chief disturbing element, was kept low so that its presence in the various alloys could hardly have had much influence. This is not an easy matter, but from the analysis it will be seen that the desired result was accomplished. The two diagrams therefore show the influence

 (*Continued on page* 708.)

Fig. 13.—*Molybdenum added by means of Ferro-Molybdenum.* (Plotted from Table 12.)

Fig. 14.—*Molybdenum added in Metallic Form.* (Plotted from Table 13.)

Full lines = Unannealed. Dotted lines = Annealed at 800° C.



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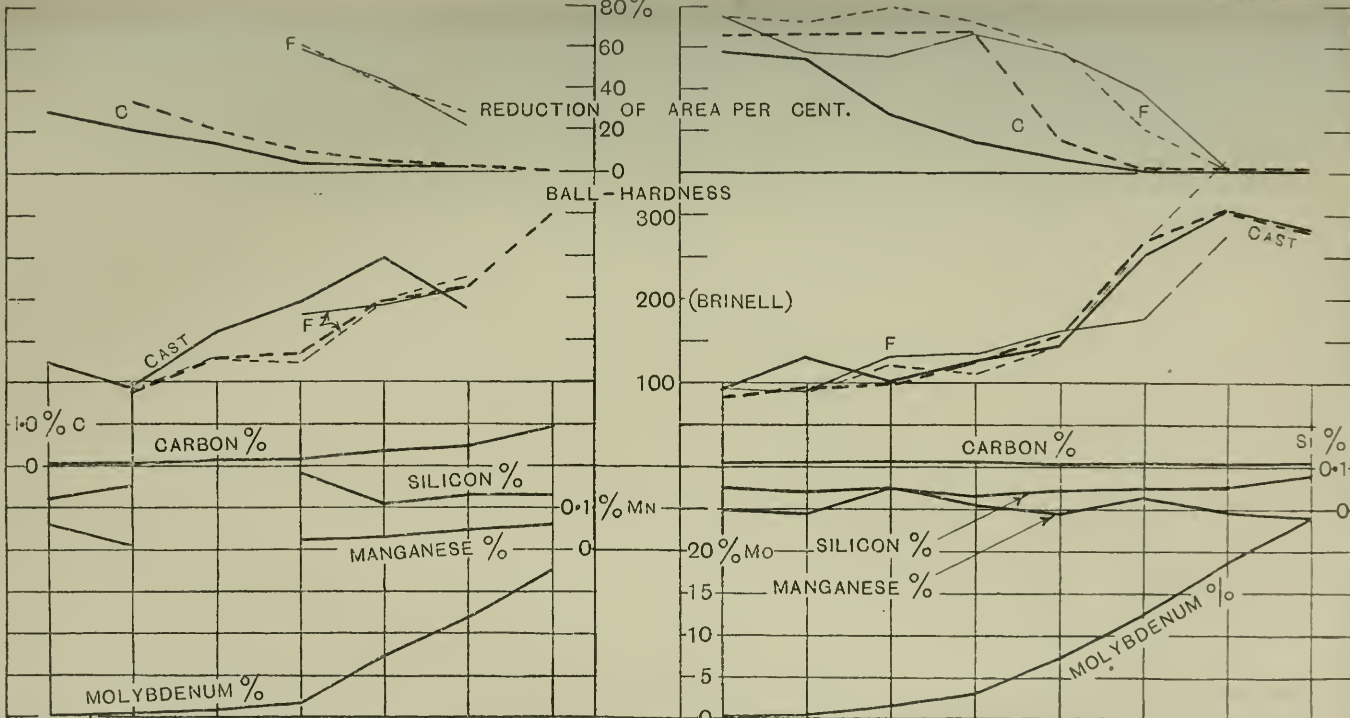

1848F	1848	1848A4	1848B	1848C	1848D	1848E		1921	1921A	1921B	1921C	1921D	1921E2	1921F	1921G
·05	·06	·11	·13	·32	·44	·92	C	·10	·10	·12	·11	·07	·09	·08	·10
·018	·05		·08	·01	·028	·03	Si	·05	·04	·05	·03	·04	·05	·05	·08
·06	·01		·02	·03	·05	·06	Mn	·10	·09	·15	·11	·09	·13	·09	·08
0·31	0·52	0·94	1·78	7·55	11·74	17·4	**Mo**	0·24	0·45	1·55	3·00	7·14	12·50	18·70	23·75

The above Tables show the analyses of fifteen steels. The points on the upper five sets of curves represent the results of the physical tests on each steel.

TABLE 12 (*continued on next page*).

Molybdenum Research.

1848 Steel Series, using Ferro-Molybdenum.

Steel No.	Analysis.				Tensile Test.				Shock Test.		Ball Test.
	C.	Si.	Mn.	Mo.	E.L.	M.S.	E.	R.A.	"C" nick.		
	Per cent.	Per cent.	Per cent.	Per cent.	Tons per sq. inch.	Tons per sq. inch.	Per cent.	Per cent.	Kgm.	Angle.	
					Cast Tests—Unannealed.						
1848F	0·05	0·018	0·06	0·31	11	18	11	29	1	Nil	124
1848	0·06	0·05	0·01	0·52	11	22	12	21	0·5	1°	95
1848A/4	0·11	—	—	0·94	23	29	6	14	2	3°	160
1848B	0·13	0·08	0·02	1·78	20	29	2	4	1	1°	194
1848C	0·32	0·01	0·03	7·55	30	44	2	3	2	4°	248
1848D	0·44	0·028	0·05	11·74	20	34	1	2	Nil	Nil	188
1848E	0·92	0·03	0·06	17·40	Too hard to machine.				—	—	—
					Forged Tests—Unannealed.						
1848F	0·05	0·018	0·06	0·31	Would not forge.				—	—	—
1848	0·06	0·05	0·01	0·52	20	21	—	—	0·5	1°	126
1848A/4	0·11	—	—	0·94	34	40	—	—	Not taken.		—
1848B	0·13	0·08	0·02	1·78	27	30	24	59	4	8°	179
1848C	0·32	0·01	0·03	7·55	35	50	19	44	5	7°	188
1848D	0·44	0·028	0·05	11·74	37	54	15	21	4	7°	212
1848E	0·92	0·03	0·06	17·40	Would not forge.				—	—	—

TABLE 12—(*concluded from opposite page*).

Molybdenum Research.

1848 STEEL SERIES, USING FERRO-MOLYBDENUM.

Transverse Test.		Tensile Test.				Shock Test.		Ball Test.	Transverse Test.	
		E.L.	M.S.	E.	R.A.	"C" nick.				
Load lb.	Angle.	Tons per sq. inch.	Tons per sq. inch.	Per cent.	Per cent.	Kgm.	Angle.		Load lb.	Angle.
		Cast Tests—Annealed at 800° C.								
—	—	Defective bar.						—	4,455	132°
—	—	11	23	25	34	1	3°	87	3,605	31°
—	—	19	28	8	20	1	3°	126	4,280	16°
—	—	17	23	5	11	1	4°	131	4,450	12°
—	—	27	43	5	5	0·5	1°	196	7,910	33°
—	—	19	34	2	2	1	Nil	212	4,890	9°
—	—	—	34	Nil	Nil	Nil	Nil	300	Not taken.	
		Forged Tests—Annealed at 800° C.								
—	—	Would not forge.				—	—	—	Not taken.	Not taken.
—	—	13	19	—	—	2	3°	90		
—	—	21	27	—	—	3	6°	127		
—	—	30	34	30	62	14	50°	121		
—	—	29	47	21	42	7·5	26°	192		
—	—	36	53	15	29	3·5	6°	223		
—	—	Would not forge.				—	—	—		

TABLE 13 (*continued on next page*).

Molybdenum Research.

1921 Steel Series, using Metallic Molybdenum.

Steel No.	Analysis.				Tensile Test.				Shock Test. "C" nick.		Ball Test.
	C.	Si.	Mn.	Mo.	E.L.	M.S.	E.	R.A.			
	Per cent.	Per cent.	Per cent.	Per cent.	Tons per sq. inch.	Tons per sq. inch.	Per cent.	Per cent.	Kgm.	Angle.	
						Cast Tests—Unannealed.					
1921	0·10	0·05	0·10	0·24	12	23	35	58	7·5	26°	92
1921A	0·10	0·04	0·09	0·45	13	24	34	55	0·5	6°	131
1921B	0·12	0·05	0·15	1·55	17	30	22	27	3·0	4°	101
1921C	0·11	0·03	0·11	3·00	18	31	14	15	0·5	1°	127
1921D	0·07	0·04	0·09	7·14	18	30	5	6	Nil	Nil	144
1921E/2	0·09	0·05	0·13	12·50	—	23	Prac. Nil	1	0·5	Nil	250
1921F	0·08	0·05	0·09	18·70	—	23	¼	Prac. Nil	Nil	Nil	306
1921G	0·10	0·08	0·08	23·75	—	22	Prac. Nil	1	1·0	Nil	280
						Forged Tests—Unannealed.					
1921	0·10	0·05	0·10	0·24	25	26	37	75	20	116° unbr.	92
1921A	0·10	0·04	0·09	0·45	26	27	31	57	20	96°	90
1921B	0·12	0·05	0·15	1·55	19	31	32	55	20	110° unbr.	131
1921C	0·11	0·03	0·11	3·00	17	34	34	67	10	29°	133
1921D	0·07	0·04	0·09	7·14	23	37	30	57	6·0	15°	160
1921E/2	0·09	0·05	0·13	12·50	28	49	14	38	Nil	3°	174
1921F	0·08	0·05	0·09	18·70	38	58	2	2	2·0	2°	275
1921G	0·10	0·08	0·08	23·75	Would not forge.						—

TABLE 13 (*concluded from opposite page*).

Molybdenum Research.

1921 Steel Series, using Metallic Molybdenum.

Tensile Test.				Shock Test.				Ball Test.	Transverse Test.	
E.L.	M.S.	E.	R.A.	"C" nick.		"No" nick.				
Tons per sq. inch.	Tons per sq. inch.	Per cent.	Per cent.	Kgm.	Angle.	Kgm.	Angle.		Load lb.	Angle.
Cast Tests—Annealed at 800° C.										
12	22	37	66	1·0	6°	Not taken.	Not taken.	84	4550	58°
11	22	42	66	1·0	5°			92	5265	99°
14	28	30	66	1·0	5°			97	5715	Double unbr.
14	29	36	67	9·0	30°			125	5840	91°
18	36	15	16	2·0	10°			156	6120	30°
—	26	Prac. Nil	Nil	2·0	4°			263	4530	1°
—	23	Nil	Nil	1·0	Nil			306	Not taken.	
—	12	Nil	Nil	0·5	Nil			280	3230	5°
Forged Tests—Annealed at 800° C.										
18	23	45	75	20	108°	Not taken.	Not taken.	95	Not taken.	Not taken.
19	24	41	72	10	30°			90		
20	29	35	79	20	103° unbr.			121		
13	30	36	72	20	99°			109		
20	36	28	59	1·5	9°			142		
32	57	11	21	1·0	Nil			269		
33	54	1	1	0·5	Nil			364		
Would not forge.								—		

of the metal molybdenum upon iron, with very little disturbing cause from the presence of other elements, namely, carbon, manganese and silicon, all of which were practically absent.

Series 1921.—Dealing with the Series 1921, in which metallic molybdenum was used, it will be noticed that as regards the tests on the material in its cast and annealed condition, the first specimen, namely 1921, containing 0·24 per cent. of Mo, shows the low elastic limit of only 12 tons per square inch, and an equally low proportionate figure with regard to breaking load, namely, 22 tons per square inch ; the elongation is remarkably good, namely, 37 per cent. The latter, however, is to some extent fictitious, as shown by the fact that the shock nick test gave only 1 kilogram, but 6° bending angle.

The specimens A, B, and C, with 0·45 per cent., 1·55 per cent., and 3·0 per cent. of Mo respectively, show very little variation in quality, which is rather remarkable, seeing that specimen C contains no less than 3·0 per cent. of Mo. It must not be overlooked that the carbon is very low, namely, 0·11 per cent., so we have still another proof of how many elements have but little effect upon iron, provided the carbon present is extremely low. In other words, as he had shown in his many Papers on iron with other elements during the last twenty-five years, it is the carbon in such alloys which is the determining factor—the special element present only acts indirectly. At any rate, in most cases a considerable percentage of a special or foreign element may be present and yet it may have but little influence, such steel containing low carbon percentage of comparatively soft nature, not differing very much from wrought-iron. This is clearly proved to be the case in 1921c, to which reference is made above. If the carbon had been increased even only to, say, 0·30 or 0·40 per cent.—that is, equivalent to mild or medium carbon steel—then the molybdenum present by indirect action would have had considerable influence in intensifying the action of the carbon present, making the particular alloy become stiffer and harder.

Even specimen D, containing no less than 7·0 per cent. of Mo, shows quite a fair amount of ductility under the tensile test, and

the elastic limit remains much the same as in the first specimen, No. 1921 or 1921A.

Dealing now with the alloys in their forged condition, specimens 1921 to 1921D—that is, 0·24 per cent. to 7·14 per cent.—here again, notwithstanding the considerable range in the percentages of molybdenum, the elastic limit remains much the same in all these specimens, namely, about 18 tons per square inch, and with a comparatively low breaking stress. The elongation is excellent, varying from 36 to 45 per cent., with a high reduction in area from 59 per cent. to no less than 79 per cent., a figure that is seldom reached by the softest steel or purest wrought-iron. The shock nick tests are excellent, 1921B specimen showing 20 kilograms, with a bend of no less than 103°, the specimen remaining unbroken. Specimen 1921D, containing 7·14 per cent. Mo, notwithstanding its comparatively high elongation, 28 per cent., shows a shock test of only 1½ kilogram with 9° bend, proving that the material, whilst stretching considerably under static test, breaks short under shock nick test.

As regards the ball-hardness, it will be noticed that there is very little difference or change between specimens 1921 and 1921D, but after that, and notwithstanding the low carbon, the ball-hardness goes up considerably, in one case 364 Brinell ball-hardness number.

Summing up the results, it would seem as if the effect of molybdenum *per se* upon iron, and without the presence of other elements, is not likely to be of importance. Its influence, however, may be found very useful in the presence of alloys containing higher percentages of carbon. However, he would not enter into this aspect of the subject, because it was being ably dealt with by Professor Arnold in his Paper, and his was a master mind in these matters. Professor Arnold's work upon the influence of carbon is most important, and will no doubt eventually offer a correct and true explanation of the many strange phenomena met with in the hardening of steel, which still puzzle the wisest amongst us.

As regards previous work which has been done upon alloys of

iron and molybdenum, the Bibliography (pages 712–713) represents some of the records, and may be useful as reference by those interested in the subject. The well-known French metallurgist, M. Guillet, contributed an excellent Paper on "Molybdenum Steels" to the Société d'Encouragement pour l'Industrie Nationale, July 1904, but in most of his products there was also quite a considerable percentage of carbon and manganese; the range of molybdenum was also only between 0·45 per cent. and 9·30 per cent. In another series the carbon present was as high as 0·70 per cent., so that these products did not show, as do those now presented, the effect of molybdenum upon practically carbon-less iron alloys. In other words, the alloys in question did not show the influence of molybdenum upon iron with other elements absent, like those now presented by the writer.

It should be added that the steels in question, experimented upon by M. Guillet, were prepared by the Société Commentry-Fourchambault at their Imphy Works. M. Guillet found that his specimens could no longer be forged when containing more than 10 per cent. of Molybdenum, also that the carbon-molybdenum-iron series containing about 0·80 per cent. of carbon ceased to be forgeable when containing above 5 per cent. of Mo. In the series now referred to, he (Sir Robert Hadfield) had been able to obtain alloys of iron and molybdenum which would forge up to 18·70 per cent. and even higher of molybdenum.

It is interesting to note that M. Guillet states the effect of molybdenum to be about four times as powerful as the somewhat analogous metal tungsten. Professor Arnold estimates (page 650) that the effect is about two and a half times, and he thought Professor Arnold was more nearly correct. The addition of molybdenum to alloys of iron in the presence of carbon has to be made very carefully. The action of the metal molybdenum is so powerful that it is very easy to produce steel which is so sensitive to hardening by water and oil-cooling or even air-cooling that during this treatment the material cracks, or rupture may take place soon or long after the product has been hardened, a dangerous quality for many classes of work where steel has to be hardened. Nevertheless, there

is no doubt that molybdenum will eventually find a place for certain specific purposes.

In order to show very exactly the influence of this metal upon iron, the reader is referred to Tables 12 and 13 (pages 704–707), also to diagrams, Fig. 13 and Fig. 14 (pages 702–703), which he ventures to think are of unusual interest, because they present side by side not only the qualities of both the cast and forged products, but the wide range of alloys from the small percentage of 0·24 per cent. to the very considerable one of 23·75 per cent. molybdenum. The influence and superiority of the forged material are brought out in a remarkable manner. In other words, it is quite clear that the original cast structures, which are, except in the lower carbon materials, brittle, persist, even after annealing, and are not easily modified. As soon, however, as the material has been forged, a great improvement is noticed, as is very clearly brought out in both the Tables and diagrams above referred to.

[For Bibliography, *see* next page.]

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The Institution of Mechanical Engineers.

PROCEEDINGS.

December 1915.

An Ordinary General Meeting was held at The Institution of Civil Engineers, London, on Friday, 17th December 1915, at Six o'clock p.m.; Dr W. Cawthorne Unwin, F.R.S, *President*, in the Chair.

The Minutes of the previous Meeting were read and confirmed.

The President announced that the Ballot Lists for the election of New Members had been opened by a Committee appointed by the Council, and the following fifty-nine candidates were found to be duly elected:—

MEMBERS.

Fincken, George,	Bristol.
Frank, Peter,	Birmingham.
Hall, Richard,	Liverpool.
Harley, Percy William,	London.
Hart, George Adam,	Leeds.
Johnson, Charles Henry,	Norwich.
Kempster, John Westbeech,	Belfast.
Pochin, Harry Simpson,	Leicester.
Pochin, Robert Francis,	Leicester.
Punter, James William,	London.
Sleigh, Edwin Henry,	Manchester.
Sykes, Frank Henry,	Derby.
Trimmer, William,	Newport, Mon.

ASSOCIATE MEMBERS.

Bates, William Reston, ...	Chuquicamata, Chile.
Bloxam, Percy, ...	Blackburn.
Butcher, Alfred James, ...	Canterbury.
Cooke, Alfred Lewis, ...	London.
Cooper, George Cecil, ...	London.
Crump, Arthur Bernard, . . .	Johannesburg.
Dobbie, Gavin Chapman Gordon, . .	Rangoon.
Dowling, William, ...	Liverpool.
Harvey, William Harry Theodore, . .	Junin.
Hepworth, Fred, ...	Birmingham.
Hind, Reginald Shuttleworth, . .	Stockport.
Isard, Arthur Percival, Captain R.E., .	Rochester.
Jackson, Ralph, ...	Manchester.
Jarvis, John Baxter, Lieut. A.O.D., . .	London.
Kilpatrick, Thomas, ...	Manchester.
Marsh, Charles Kenneth, . . .	São Paulo.
Meiklejohn, James Henderson, . .	London.
Murray, Tom, ...	London.
Nell, Leonard, ...	Nigeria.
Pile, Walter Devereux, . . .	Rio de Janeiro.
Prothero, Edwin George, . . .	Birmingham.
Rendell, Henry Thomas, Captain A.S.C.. .	B.E.F., France.
Sanderson, George Dalgleish, . .	Perth, W. Australia.
Scott, George Herbert, ...	Ferrol, Spain.
Sowerby, Philip, ...	London.
White, Patrick Thomas, ...	Limerick.

GRADUATES.

Brooks, William Edwin, ...	London.
Bryant, Cyril, ...	Lincoln.
Fitzgerald, Thomas, ...	Birkenhead.
Harrison, Robert Cecil, . . .	Doncaster.
Hay, Stanley Gardiner, . . .	Brighouse.
Haynes, Norman Pilkington, . . .	Stony Stratford.
Jennings, Mark, ...	Bury St. Edmund's.
Light, Raymond Ernest, ...	Eastleigh, Hants.
McClunan, Eric, ...	Lincoln.
McKinty, James, ...	Devonport.
Mather, Raymond Alexis, . . .	Woolwich.
Mitchell, Reginald Joseph, . . .	Stoke-on-Trent.
Owen, Sidney, ...	Barry Dock.
Pounder, Cuthbert Coulson, . . .	Colchester.
Reddick, Richard Faithful, . . .	Woolwich.
Tanner, Charles, ...	Newbury.

Turner, William Henry, . . .	Nottingham.
Verity, George, ...	Birkenhead.
Walker, Edwin, ...	Sheffield.
White, Henry Grinsted, . . .	Weymouth.

The President announced that the following five Transferences had been made by the Council:—

Associate Members to Members.

Marshall, William Johnstone, ...	London.
Powell, Llewellyn Henry, ...	Glasgow.
Reeve, Edward, ...	Birmingham.
Taylor, William Thomas, ...	Lytham.
Waldron, Frederic Barnes.	St. Helens.

The following Paper was read and discussed:—

"Engineering Colleges and the War"; by R. Mullineux Walmsley, D.Sc., F.R.S.E., Principal of the Northampton Polytechnic Institute, London, and C. E. Larard, *Member*, Head of the Civil and Mechanical Engineering Department, Northampton Polytechnic Institute, London.

The Meeting terminated at Half-past Seven o'clock. The attendance was 83 Members and 38 Visitors.

ENGINEERING COLLEGES AND THE WAR.

By R. MULLINEUX WALMSLEY, D.Sc., F.R.S.E.,

Principal of the Northampton Polytechnic Institute, London,

and

C. E. LARARD, *Member*, Head of the Civil and Mechanical Engineering Department, Northampton Polytechnic Institute, London.

Anyone who during the last few years had followed closely the developments of armaments could have predicted that, as has actually happened, the next great war would be essentially an Engineers' War, and that the engineering aspects of the war would not be confined to the old distinctions which separated military from civil engineering. These conclusions were inevitably pointed to by the developments which have taken place in mechanical transport, terrestrial, aerial and naval, both on the surface and under the sea; in ordnance and other implements of war for naval and field operations necessitating workshop tools and trained engineers; in telegraphy and telephony with or without interconnecting wires; and in all kinds of new optical aids.

It was therefore a national duty from the military and naval, as well as from the educational, point of view that the equipment and

staffing of Engineering Technical Colleges and their organization should be brought to a high state of efficiency as a preparation for national defence, if need be, against the contingency, which was not very remote, of this country having to face a European War.

On the outbreak of the war it was inevitable that the work of the technical colleges in relation to it should be put upon its trial, and that the colleges should be asked to prove that the large, though insufficient, sums of money spent on their equipment and staffing were justifiable from the practical engineering as well as from the purely educational point of view.

The object of this Paper, however, is not to examine the whole of the general questions which obviously suggest themselves in this connexion, but to deal more especially with what is being and can now be done by the technical colleges to assist the country in its endeavours to win through. The Authors, therefore, venture to bring before the Institution the present Paper dealing with such matters and with the distinct object of raising questions for discussion. They venture to hope that the opinions and suggestions of practical engineers and of expert engineering teachers, the expression of which may be expected to follow the reading of the Paper, will prove of considerable value towards the attainment of the end which all have in view.

For convenience of reference, the Paper is divided into the following sections and sub-sections, though it may be said at once that close water-tight divisions between the different parts are not possible nor perhaps even desirable :—

1. *Munitions Work in Technical College Workshops :—*

   (i) Equipment available.
   (ii) Personnel : staff, students and others.
   (iii) Conditions under which the College Workshops should be utilized.
   (iv) Kind of work which can be undertaken.
   (v) Organization of this work.
   (vi) Work actually undertaken in the College Workshops.

2. *Training of Munitions Workers and War Workers generally:—*

    (i) Summary of what is being done at present in Technical Colleges.

    (ii) Training carefully selected hands on the direct production of munitions under manufacturing conditions.

    (iii) Whether, and under what circumstances, the manufacture of munitions is preferable to training munitions workers.

3. *Other Engineering War Work in Technical Colleges.*

1. Munitions Work in Technical College Workshops.

(i) *Equipment available.*—Many of our best technical colleges have well-equipped workshops provided with valuable modern tools of precision, such as universal grinding machines, tool-makers' machines, capstan and turret lathes, universal milling machines, gear-cutters, etc. Where such equipment is available, there can be no doubt that the best use to which it can be put is in the manufacture, either directly for Government Departments or through the local Munitions Committees, of munitions of all kinds, including the very numerous ancillary details necessary for the completion of the equipment of the Navy and the Army as fighting forces.

Many practical engineers and some engineering professors have in the past looked with disfavour, almost with contempt, on the college workshop, and have doubted whether any serious work or instruction of real value can be given in it from a practical engineering point of view. This doubt, we are sorry to say, is in many cases the result of the amateurish workshop equipment and instruction given in a number of technical schools, excluding those referred to in the preceding paragraph. Owing to the fact that they have gone on year by year installing cheap examples of old types of machines, fit only for the rough machine operations established long ago in the days of James Watt and of the machine developments inaugurated by Whitworth, the assistance which these schools can give

to the country in the present crisis is necessarily different from that which can be given by the better equipped colleges which have suffered largely from these ill-advised and pretentious attempts of other institutions at teaching so-called engineering workshop practice.

This, however, is neither the time nor the place to deal with the position of the college workshops in their several educational aspects; but it is of urgent importance that their equipment and staff should be utilized to the best advantage in the service of the country during the present national crisis, irrespective of educational, personal, or even of local considerations. In this utilization, the type of the equipment which has been accumulated in the past must necessarily be a determining factor as to the special work to be undertaken.

As regards the amount of equipment available of one type or the other, it may be noted that the number of technical colleges and schools in the United Kingdom comprised in the membership of the Association of Technical Institutions is ninety-six. The list is nearly but not quite exhaustive, for it does not include the University Engineering Schools in London, and similar schools in some of the provincial Universities. There may also be some minor technical schools not included. Altogether, not fewer than 112 educational engineering workshops or sets of workshops are in existence, and of them about 25 fall into the higher category referred to above as being more or less well equipped with modern productive tools.

(ii) *Personnel: Staff, Students and Others.*—As regards personnel, there are on the staffs of many of these engineering colleges and schools, including some of those which may be poorly equipped with modern tools, skilled instructors and workmen trained in good commercial workshops and familiar with and capable of operating modern up-to-date tools. There are also large numbers of skilled and semi-skilled engineering students who may be employed, and these may be and are in many cases supplemented by any outside skilled workmen obtainable.

(iii) *Conditions of Utilization.*—The question of immediate importance is under what conditions and in what manner the workshops of our engineering colleges can be made of use to the Naval and Military Authorities. This, as remarked above, depends to a large extent upon the equipment of the particular workshop under consideration.

Where there is already a collection of modern tools of precision as well as of the other tools suitable for the roughing out and finishing of parts of munitions and military apparatus, the Authors have no doubt but that the best course to pursue is not to attempt to combine educational work with production, but to organize the workshop as a factory workshop, and staff it under the direction of the well-trained staff which in such a case will be available on the spot, employing also such students as are available and are likely to be useful in the work. In addition, skilled workmen should, whenever possible, be imported from the outside, if such workmen can be found, but the experience of the last few months shows that it is difficult to obtain many of this type of workmen, namely, those who can work to the highest degree of accuracy required in finishing inspection gauges and in other high-class productive work. The available supply appears to have been quickly absorbed in the early days of the present development of munitions works.

An alternative method in large centres would be to assemble a selection of tools from the different colleges in the area under one organization, and at a convenient centre for the purpose, rather than to distribute the work amongst the colleges, no one of which may be competent to deal with it on broad lines. The object of this centralization would be the carrying on of the best type of work mentioned in the next sub-section. Undoubtedly also, much can be done by grouping and concentrating special tools in large areas for the manufacture of some special work, such as shell bodies. If, for example, the Education Authorities in a large area were to concentrate the heavier lathes, certain furnaces, presses and other suitable plant in one centre, together with the necessary staff, it would be quite possible to obtain an output of from 200 to 600 shell-bodies a week, and that with tools which in many instances would

otherwise be doing relatively unimportant work or be lying entirely idle.

In another centre, furnaces, pyrometers, and the suitable staff may be concentrated to deal with the special hardening operations for gauges before the final finishing work, such as grinding and lapping, is done. Many manufacturing engineering firms, as well as some technical colleges, on first undertaking the manufacture of gauges, have found considerable difficulty in dealing successfully with the hardening of cast or tool steel for gauges, resulting in large waste of material, and, what is more valuable, time. Gauge-makers will realize the great importance of the above suggestion in the case of firms or institutions taking up gauge manufacture for the first time.

Then, again, educational institutions, have an Artistic Crafts Department with special craftsmen on the staff. These departments might usefully be employed as centres for the stamping or engraving of gauges and other work. The Authors can state from direct experience that this work can be carefully and expeditiously done by such a department.

Where, owing to the unsuitability of the equipment or for other reasons, the technical college authorities are unable to engage in the manufacture of munitions or to employ suitably the valuable tools under their charge, they should be required to hand over such tools, either on loan or purchase, to Government Departments or "Controlled" Munitions Works urgently requiring them.

In all cases in which the equipment utilized has been largely derived in the past from the expenditure of public money, that is where the college workshops are being directly utilized as recommended or where there is a centralization scheme, the conditions under which work can be undertaken appear to the Authors to be fairly obvious.

In the first place, the work undertaken should be on orders received directly either from the Local Munitions Committee or from Government Departments. The conditions under which it should be undertaken should be the charging to the Government of actual out-of-pocket expenses, including such wages as are directly paid in connexion with this work, but excluding the full-time

salaries of the expert members of the staff who are engaged upon it. Incidentally, it may be remarked that these full-time members of the staff should, if the work is to be effective, be giving to this commercial production a number of hours per week largely in excess of the hours required for educational work. This extra time, which is not less than from ten to twenty hours per week, has up to the present in some institutions been voluntarily given by the engineering staff, who have fully realized that, not being charged against munitions, it is a fair equivalent of the time which would under ordinary teaching conditions be employed by them in preparation work outside of the scheduled time for routine college work. Any students engaged on the work should be paid such wages, representing the commercial value of their work, as may be determined by the expert opinion available. These wages would usually be on an hourly basis, though, when the nature of the work allows of it, piece-work rates should be fixed and the work done should be paid for per piece with the view of obtaining an increased output at a reduced cost. Students who have had some or no previous commercial workshop experience are, of course, of the grade of apprentice learner or improver from the shop point of view, and are not to be regarded as skilled workmen.

Under these conditions it is submitted that the total cost of production chargeable to the Government should not, for all the college workshops considered together, be in excess of the cost in well-equipped commercial factories; but it is obvious that if this method of charging for the work be adopted, then no orders should be taken from private firms, as this would lead to the exploitation of public property for private profit.

(iv) *Munitions Work which can be undertaken by the College Workshops.*—Assuming a well-equipped workshop and a capable engineering staff assisted by students and additional workmen with good workshop experience, the kind of manufacturing work which can be done in sufficient quantity to be of real war value may next be considered.

Taking first the highest type of college workshop equipped with

modern automatic tools and representative precision machines, together with the necessary gauges and ultimate standards of measurement, perhaps the most useful work at the present time from the war point of view is the manufacture of gauges—both inspection gauges and shop gauges—for which there is a very pressing need. As in the manufacture of these gauges the limits of error allowed vary from, say, $\pm \frac{3}{10,000}$ inch to $\pm \frac{6}{10,000}$ inch, depending on the type of gauge, and special operations such as annealing, hardening, stamping, grinding and lapping—all necessitating special skill—are required, it is vital, if wasteful expenditure and disappointment are to be avoided, that what is meant by a "gauge" should be clearly understood. As a workshop operation, even this degree of accuracy is eclipsed in the case of gauges for small-arms, and gap-gauges which are worked to simple check gauges, where a small fraction of $\frac{1}{10,000}$ inch can be detected by the skilled worker.

The first criticism which will at once suggest itself to a casual reader is, "Yes, it is all very well to talk about gauge-making in the technical college workshop, but how will you obtain the skilled workers, who must be of the highest type, when there is such a great and unsatisfied demand for gauge-makers in the arsenals and munitions factories? Further, even many so-called skilled workmen can never be trained to be good gauge-makers, for it is a case of 'many are called, but few chosen.'" Now, it must be granted at once, and will be shown more fully presently, that for the machine operations involving the use, say, of a universal grinder, or of a good lathe for screw gauge making, a highly-skilled man is required, thoroughly at home with the use of machine-tools, and possessing, in addition, the necessary temperamental faculty of perceiving by touch and gauge very small differences of dimensions. Quite a number of institutions have such men on their regular teaching staff, and not to use such highly skilled ability at the present time is a national sin. Further, many engineering students attending the technical colleges have had previous workshop training, and from actual experience it can be asserted that a few possessing the necessary faculty can, with a little instruction and close

oversight, be so trained that they quickly pick up the special grinding and lapping operations necessary in the final stages of gauge-making.

Then, again, there are very numerous details wanted for gun and small-arms work requiring not only the use of capstan lathes and operators, but of the higher type of workman able to use gauge and micrometer in milling, screw-cutting, grinding, etc., and for this kind of work also the well-equipped college workshop can be, and is being, made use of.

Turning next to somewhat poorly-equipped workshops, these can be utilized, provided the necessary tools of the ordinary type are available, with students to work them. They can be employed, for example, on rough machining for gun and carriage details, details for aeroplanes, such as plates, pins, bolts, stays, etc., and on many other operations requiring only somewhat crude workshop skill. Experience, however, up to the present has shown that this roughing work is difficult to obtain from the sources indicated, for the following reasons :—

First, the roughing and often the finishing in the arsenals and munitions factories are for the most part done cheaply on automatic and semi-automatic machines, and it is the finished article, worked very often to the thousandth or half-thousandth of an inch, that is required in quantity.

Secondly, few munitions firms, and certainly none of the Government arsenals, are able, owing to heavy pressure of work on the controlling staff, to place orders for simple roughing work to be returned for finishing, with an individual technical college of limited capacity whose output would be so comparatively small as to be almost a negligible quantity.

It is here that the Local Munitions Committee, or the Local Education Authority in the case of large areas with several technical colleges properly organized, can be of use even if it be considered undesirable to develop a centralization scheme such as has been recommended above. Orders for finished units of work in quantities should be freely placed with these authorities by the Government Departments. The authorities acting as distributing and collecting

agencies would then place orders and material with the various technical colleges for specific operations. Tools at one institution would be found capable of doing only the crudest of rough machining to ordinary callipers, and the institution should be required to do that work, which would then be collected and passed on to another institution capable of dealing with the somewhat finer and more skilled operations ; finally, it would be finished at the one or two institutions capable of dealing with the most accurate workshop operations.

In the hope that it may be of assistance to the public bodies referred to and others, the Authors, in Appendix II (page 751), have scheduled in detail the chief particulars which should be ascertained as a basis for the decisions to be arrived at. So far as the Authors have been able to find out, this system, or some modification of it, does not seem as yet to have been adopted. For its proper working, the Munitions Committee or Education Authority would require to have a well-qualified and trained man, with a bed-rock knowledge of modern workshop methods, detailed for this special work, who could give his full time to its organization and administration, and not, as is sometimes the case, be employed on other work. Skilled advice through a large committee of local engineers is a great step in the right direction, but what is wanted in addition on these committees is the full-time organizer with executive authority and with full responsibility for seeing things put through expeditiously.

The question of cost for work carried out in this way, as compared with that produced by automatic machinery, does not bulk largely when it is remembered that the labour may be largely patriotic and unpaid, that many munitions factories cannot obtain nearly the full number of automatic machines they require, and that many institutions working together can produce by these less modern methods work of considerable value in a far from negligible quantity.

(v) *Organization of the Work.*—Dealing next with the question of suitable organization for the rapid production of munitions in college workshops, it should be first and chiefly insisted upon that only full-time work is of value. Nothing can be more lamentable,

or perhaps even ridiculous, than to attempt to undertake, as has unfortunately already been done in some places, the manufacture of munitions at odd times during a regular full-time course of engineering college work. The Education Authorities have to make up their minds that if this thing is worth doing at all, it is only worth doing well, and it is one of the sacrifices demanded by the stringency of the present crisis that at least some of the educational work, and from the conditions that of the higher type, has to be set aside for the present, so that the personnel, both students and instructors, as well as the material equipment, may be freed for national service. It may be remarked, parenthetically, that the lower type of educational work, such as the first year's day courses in the colleges, may be continued, since the young students fresh from school and under military age are rather a hindrance than a help in the workshops, and for the time, at any rate, their instruction may be undertaken by teachers who are not necessarily so well-versed in actual workshop operations as their more skilled colleagues. It is, of course, understood that workshop practice forms a small part of a first-year's course at a technical college, and can be given in other shops not used for munitions work. It being granted, then, that only full-time work is contemplated, it is essential that it should be organized in accordance with the practice which in some form or other now obtains in the best workshops.

In the first place, a reliable system of cost-keeping is essential, and although the various institutions will, perhaps inevitably, adopt methods suitable to their particular circumstances and differing in details, yet it is important that each institution should start on a clearly-defined system.

There will, in general, be several, and sometimes many, operations required to produce the finished article, and it is of the utmost importance, if the work is to be done as quickly and cheaply as possible, that the men should be properly grouped, and that each man should as far as possible be confined for a reasonable time to one operation only. Thus, for example, if numbers of a particular type of gauge are to be manufactured requiring, say, twelve operations, then if possible twelve men, each on a distinct operation, should be

employed. This system is, of course, quite the practice in a well-organized engineering factory, but in some university colleges and technical schools, attention to the business side of practical engineering and of modern workshop methods is conspicuous by its absence.

The records for the cost of such work are best obtained by some system of job-ticket and job-cost cards, which when completed will enable the costs of any or of all of the work turned out to be readily determined. An example of such a job-ticket, which may be a printed card measuring 6 inches by 4 inches, is shown on the opposite page, and an example of a job-cost card which may also be in the form of a card 6 inches by 4 inches is shown on the same page. These are so drafted as to form part of a good system, whereby the costs of all work may be arrived at.

A job-ticket should be issued to each workman on commencing a particular operation for a number of identical parts, and given up by him, with all the information filled in, when the particular operation is finished, together with the work done. He will then be given another job-ticket and other parts to be worked on the same (or another) particular operation. All the job-cards for a particular job-number, taken together, will give the cost of direct labour for the job in quantity. These labour costs will be transferred to the job-cost card for the several operations of the particular work.

In addition to direct labour, there will be the indirect charges or shop charges, which will include :—

Cost of power.

Depreciation of tools based on the life and scrap value.

Cost of small tools, oil, and the many other incidentals required.

Cost of light, gas, water, etc.

Establishment charges, which in ordinary engineering works form a not inconsiderable item, should not be charged, remembering that these charges would exist if no munitions work were undertaken, and have already been paid for from public funds. Moreover, the usually heavy item of drawing-office charges is most frequently eliminated by the necessary working drawings being supplied with the order. To charge any proportion of institute establishment charges

JOB TICKET

M.E.D. ORDER No. _ _ _ _ _ _ _

OFFICIAL REFERENCE _ _ _ _ _ _

WORKMAN _ _ _ _ _ _ _ CHECK No. _ _ _ _

DATE AND TIME ISSUED _ _ _ _ _ _

DATE AND TIME RETURNED _ _ _ _ _ TOTAL HOURS _ _ RATE _ _ _ _

NAME OF PART _ _ _ _ _ _ PART No. _ _ _ _ _ _

No. OF PARTS ISSUED _ _ _ _ No. ACCEPTED _ _ INSPECTED BY _ _ _ _

No. OF MACHINE _ _ _ _ _ _

OPERATION _ _ _ _ _ _ No. _ _ _ MATERIAL _ _ _ _ _

DATE	HOURS	DATE	HOURS	DATE	HOURS	REMARKS

Note.—This card to be handed in when the particular operation is complete, and must not on any account be taken away, but hung on the board required whilst the work is in progress.

JOB COST CARD

M. E. D. ORDER No. _ _ OFFICIAL REFERENCE _ _ _ _ NAME OF JOB _ _ _ _ JOB No. _ _

OPERATION No.	OPERATION	HOURS		DIRECT LABOUR				SHOP CHARGES				MATERIAL
		MACHINE	HAND	RATE	AMOUNT			RATE	AMOUNT			(FURTHER DETAILS ON OTHER SIDE)
					£	s.	d.		£	s.	d.	

KIND _ _ _ _ _ _

FINISHED WEIGHT _ _ _ _ _

ROUGH WEIGHT _ _ _ _ _

PRICE RATE _ _ _ _ _ _

	£ s. d.
MATERIAL	_ _ _ _
D. LABOUR	_ _ _ _
S. CHARGES	_ _ _ _
+ %	_ _ _ _
WORKS COST	£ _ _ _

DATE _ _ _ _ _ _

to munitions would, under the conditions of the work, result in making the manufacturing price prohibitive, and is undesirable from other points of view.

In connexion with the question of the extent, if at all, to which the salaries of the engineering teaching staff should be charged to munitions work, we are glad to note that the Governing Bodies of some institutions feel it their duty to allow their staff, in time not urgently required for other work, to engage upon munitions work without charge to the cost of the work. If this were not done, the utmost that could be properly charged to munitions work, where the staff are engaged on this work, would be workshop value of the individual on similar work in a modern engineering factory. This workshop value will in some cases be more, but in many cases less, than the salaries paid for teaching work. There is then the difference, plus or minus, to be considered. Generally, where members of the teaching staff have joined the military forces, the Governing Bodies have, where army or naval pay is less than the institute salary, made good the deficiency. In cases where the teacher earns more as a worker on munitions, he should be allowed to keep the increase. On the other hand, where either whole or part salary is charged directly to munitions work, there must necessarily arise the question as to whether a corresponding reduction of grant to the institutions from public funds ought not to be made; for it is obvious that to charge salaries to munitions work without a corresponding reduction of grants from public funds would result in the taxpayers and ratepayers paying twice over. The simplest solution, and the one to which least objection can be taken, appears to be to allow engineering teachers in public institutions to engage upon munitions work without any charge for their services being made against the cost of such work. Exception may be made, however, where overtime is worked, for which the proper workshop value should be paid to the teacher. This procedure will simplify matters and avoid the cumbersome business (which must operate to the detriment of the rapid and urgent manufacture of munitions) of transfer and readjustment of grants as between the Imperial and

Local Education Authorities and the Governing Bodies of our Technical Colleges.

(vi) *Munitions Work actually undertaken in the College Workshops.*—The Authors propose next to give some indication of the munitions work which is at present being done in the engineering workshops of the different Technical Colleges, together with some idea of the actual conditions under which such work is being undertaken. It is hardly necessary to state that it is inadvisable, for military reasons, to be too specific in details with respect to the exact kind of work or the precise locality in which such work is being carried out. To do so might bring the Paper under the ban of the Censor. Most of the London Polytechnics and the technical institutions under the direction of the Education Committee of the London County Council are either directly engaged in the manufacture of munitions, or are giving some form of training to munitions workers. The same holds in London and the provinces as regards some of the University Engineering Departments, the larger Technical Schools, and also some of the smaller ones.

Dealing with the London Educational Institutions first, and, in this section only, with munitions work, by far the most important of the work undertaken is the manufacture of numerous types of gauges which require to be finished with a very high degree of accuracy. The output in this respect is considerable, and would astonish some of those engineering critics who look with disfavour on the college workshop. In addition, both in London and the provinces, very numerous details are being manufactured for naval and military work of various kinds, such as shell-bodies, gun-mountings, parts for motor-lorries, aeroplanes, naval guns, fuses, adapters, *gaines*, details for small-arms, armourers' details, and much other work, all of which is being effectively carried out by these college workshops. In addition, some of the workshops are manufacturing small tools, jigs, etc., for neighbouring munitions factories. The particular type of work undertaken in any institution depends, as has just been shown, on its equipment and the conditions under which the work is organized and carried out.

An important question is the cost to the country at which this work is being done. Some institutions will no doubt be able to show that they can manufacture at a price which compares favourably with that of the outside manufacturer. In other institutions the cost price may well, because of the conditions, be greater than the proper market value. On account of urgency extra cost may be faced without misgiving, provided it is not unreasonable, as it is output which matters first and cost afterwards. It cannot be disputed that, if a college workshop can turn out work up to specification in sufficient quantities at a reasonable market price, then that workshop is doing good work under difficult conditions, and that if it be possible for one good workshop with good facilities to do such work, it is possible for others under proper organization to do likewise.

It will be worth while at this stage to consider how orders for such work are placed, and the kind of agreement arrived at by different authorities as to payment for work delivered. Orders for work are placed by Government Departments, either directly with the colleges which have inspired sufficient confidence to justify such a course, or with the local Munitions Committee who are acquainted with the full circumstances, and who can act as distributing agents for the Government Department concerned. Again, some institutions, both in London and the provinces, act as sub-contractors for details urgently required to the large armament firms or to smaller firms engaged in the manufacture of munitions. In another part of this Paper it is pointed out how undesirable this latter course is. The methods of charging for the work vary considerably, and depend upon whether the order is received directly from the Government Department, from the local Munitions Committee, or from one of the armament firms or other munitions works.

The most desirable conditions under which work has been accepted, whether that work is done for a Government Department or for the local Munitions Committee, is practically the cost price to the Governing Body of the work done, over and above any outgoings which would have been incurred if the work had not been

undertaken. This includes the cost of material, direct labour and shop charges, including the cost of power, lighting, heating, etc. Hitherto, in such cases, orders have not been accepted from private firms, and it is proposed not to accept such orders so long as the necessary work is forthcoming from the Metropolitan Munitions Committee, or one or other of the Government Departments. The objections to accepting orders from private firms are set forth above, but it must not be overlooked that munitions, wherever manufactured, are very urgently required.

Technical Colleges undertaking work for private firms must necessarily agree at the very commencement with respect to the financial conditions under which the work is undertaken. In some instances contracting parties have agreed on a definite price for each piece of work to be done. In other instances the cost price, with or without establishment charges, has been agreed to, but the conditions vary considerably in relation to the many technical institutions which have undertaken munitions work. Agreement to pay cost price, plus shop and incidental charges, necessarily implies a considerable amount of confidence by the Government Department or firm placing the order. The workshops of one large provincial institution are being run entirely by orders from a prominent firm engaged on munitions work, which agreed to furnish all material, pay the wages, plus other charges to the extent of 100 per cent. of the wages paid on the work, with the proviso that the agreement can be terminated at any time. Another very large provincial institution engaged on munitions work for a large armament firm is charging cost price in material and wages, but nothing for power or establishment charges. To meet some of the objections urged above, having reference to the danger of exploitation for profit by private firms, it may be argued that all these firms are "controlled" firms working with a limitation of profit for the end that all have in view. Thus, if costs are slightly reduced and work done cheaply in particular college workshops, the result will stand as a set-off against the cost, much higher than the market price, at some other institutions working on an actual cost price basis.

Reference has been made elsewhere in the Paper to the desirability of grouping and concentrating tools collected from the technical colleges in large areas in a suitable building, for the purpose of manufacturing munitions, and it is interesting to note that this has to some extent been done by the Education Department of the London County Council, and probably at some institutions in the provinces. Full details of the results of this work are not yet available, and a report to date, fully setting forth all the details and the difficulties encountered, as well as the effective work done, would be interesting and probably instructive.

The Authors have endeavoured, from statistics available, to form a rough idea of the extent to which technical colleges are dealing with the munitions problem, and have estimated that about one-third are employed on the manufacture of munitions in some form; another third have been training munitions workers; and some of the remaining technical colleges have dealt with the problem by the supply of their workshop tools to munitions factories.

2. Training of Munitions Workers and War Workers generally.

(i) *Summary of what is being done at present in Technical Colleges.*—A fair number of technical college workshops are being utilized for the so-called training of munitions workers, and the training given depends essentially on the type of workshop equipment, as well as upon the technical or teaching staff which can be set aside to deal with this work. As pointed out above, a very large proportion of these school workshops have facilities representing more the older type of engineering workshop and workshop practice, but the more modern colleges have in many instances modern tools of a high order of excellence with the necessary staff competent to use them.

The instruction courses given are remarkably varied, both in relation to the duration of the course and the quality of the work dealt with. Thus we find one technical college proposing to give instruction to intending munitions workers for a fee of 5*s.* for ten hours' instruction, and to train women for the measurement work in shell manufacture. Another technical institution has arranged

instruction courses in screw-cutting in connexion with the Amalgamated Society of Engineers, who supply eight of their members as instructors for lathe work. At another institution a mixed class of girls, youths, and men receives instruction on the ordinary types of machines, in the hope that they will be capable of employment by a munitions firm for the manufacture of shell-bodies after a fortnight's instruction. Longer courses of instruction of from four to six weeks are undertaken by institutions, large and small, for considerable numbers of workers in the expectation that they may be placed with munitions firms afterwards. Evening instruction is also being given to inexperienced men and girls, in the hope that they may be qualified for admission into a munitions works after anything over a fortnight's training.

These examples are sufficient indication of the fact that instruction courses are open to the general public for periods of time which in many instances are totally inadequate to produce any useful result. Comparatively few of the institutions working under these conditions are prepared to offer any guarantee of subsequent employment to those being trained, and the Authors believe that only a very small proportion of workers so trained at the outset ever saw the inside of a munitions factory. The fact was, that the terms "munitions work" and "munitions workers" were very elastic and excelled the word "Mesopotamia" as phrases to conjure with. A "munitions worker" apparently might be anything from one who is required to do routine work of such an elementary nature that skill and rapidity can be acquired in a few hours by anyone with intelligence and enthusiasm, to the most highly-trained workmen whose deftness and dexterity can only be acquired by long experience. A "certificate of proficiency" in munitions work may therefore mean little or much, and the proficiency certified requires to be very specifically defined. Better considered courses of instruction than those alluded to are, however, being offered and taken advantage of at Technical Colleges in London and in the provinces. The Education Department of the London County Council has undertaken a considerable amount of work in connexion with the training of munitions workers. Many of the tools and facilities at

the various junior technical schools under the Council have been transferred and centralized, and very definite instruction in workshop practice is being given to both sexes. It would be interesting in this connexion to have a report from the authorities as to the success of this scheme.

Apart from the instruction which is being given to inexperienced workers, a good deal is being done in connexion with the supplementary training of skilled and semi-skilled workmen. Courses of instruction are offered in London and various parts of the country to skilled mechanics, fitters, turners, etc., some of whom are members of trade unions and have been brought up on the old English workshop lines. We find at one large provincial centre a complete plant for the turning out of shells, and we understand that works in the district engaged on munitions send their workmen to see the process of manufacturing from start to finish. Another prominent institution, acting under the local Munitions Committee, has received thousands of names of persons, many of whom are semi-skilled and many unskilled, who wish to receive instruction in the use of modern machine-tools and measurements for shells and gun manufacture. Then again, more than one institution is combining instruction work with a certain amount of munitions manufacture, but it is doubtful whether, even given semi-skilled and skilled labour of a certain type, much training can be done concurrently with the effective manufacture of munitions.

It has recently been proposed by certain of the Educational Authorities to add to their present equipment various modern machine-tools of a very elaborate character with a view to training selected mechanics or others in the use of these particular tools. It is very doubtful whether such tools can be obtained from the manufacturers under present conditions in time to be of any use, and even if they could be so obtained, whether this is the best way to utilize them. All tool manufacturers and tool factors have received definite instructions from the Ministry of Munitions to hold such new tools, as they may make or obtain, for disposal to munitions works, which would of course include college workshops directly engaged on the manufacture of munitions. One of the best

of the technical schools in the country is giving definite instruction in capstan-lathe work, tool-setting on automatic machines, and the use of gauges. All these examples go to show that a very considerable amount of work is being done, and it is proposed to extend this work for the training of unskilled, semi-skilled, and skilled workers. It cannot be gainsaid that it is possible to do a considerable amount of useful work, providing such work is undertaken with a clear knowledge of the requirements, possibilities, and limitations, and given that a certain definite object is in view, and also given the certainty of immediately placing the men so trained in munitions works. This question is still further considered later.

(ii) *Training carefully selected hands on the direct production of Munitions under manufacturing conditions.*—There are, we believe, in the United Kingdom thousands of men with some training, more or less thorough, as fitters, turners, machinists, erectors, clockmakers, artistic craftsmen, etc., who are of various ages and who are not yet employed in the manufacture of munitions. These men have received their training and experience in the old-fashioned type of shop of the non-specialized kind, or in shops not requiring the costly and elaborate equipment of modern machine-shops. These are shops in which universal grinders, automatic machines, gear-cutters and even milling-machines are either few in number or are conspicuous by their absence. The workmen referred to have been earning, and have deserved to earn, fairly high wages before the dislocation caused by the war began to tell, but since then there has been some difficulty in finding work for some of them. It is obvious that such men should not be offered wages below those to which they have been accustomed, but the difficulty is to find the intermediate work at which such wages can be earned.

To explain how this very curious state of affairs has arisen, namely, the existence of a large body of skilled mechanics for whom, notwithstanding the present abnormal demand for engineering labour, there is difficulty in finding proper employment, a brief digression may not be irrelevant even for professional engineers, some of whom may not, in the rush of modern work,

have followed up this particular phase of engineering development very closely. The conditions under which mechanical engineering has been carried on in the past and the necessity for economic production have during the last two decades undergone remarkable changes, amounting to a revolution in workshop methods of manufacture, organization, and management. Machine operations have become more and more specialized to produce greater accuracy in dimensions and finish and greater output, and, by the use of the limit gauge system, interchangeability of parts.

Sir (then Mr.) H. F. Donaldson stated before this Institution on 15th February, 1901, in the discussion following the reading of a Paper by one of the Authors' predecessors at the Northampton Institute, that "The introduction of automatic machines was due to the high cost of labour and the absolute necessity of getting work done without having to expend more in wages than was necessary, and to allow of the manufacturer having the possibility of adopting more or less unskilled labour in many productions. . . . The result aimed at was to get as large and as cheap production as possible. . . . English machines had attained the character of a very high standard of excellence, but they required brains, not only to produce, but also to work them. . . . With the automatic machine brains were required to start it, but after that the attendance did not need to be of the same calibre as was required at the start; the watching, the keeping in order, and the feeding of the machine could be done by a less expensive man."

Thus the general trend of recent years has been to replace costly hand-finishing and the costly work done on the older types of English tools by machines which in time have become more and more automatic, with greater accuracy of the work done and with greatly increased output. Hence the developments in the manufacture of the many types of milling-machines (largely replacing shaping-, planing-, and slotting-machines and hand-labour), cylindrical and disk grinding-machines, turret and capstan lathes (replacing the lathe and skilled turner), jig work for increased and accurate productions, the use of limit gauges instead of the micrometer and calliper (making for interchangeability

and increased output, so important for the manufacture of guns and small-arms); these in their turn have led to the development of special tool-makers' machines and the modern tool-room equipment.

Some of the results of these developments have been :—

(1) Largely to replace costly workmen by costly machine-tools.

(2) To create two distinct classes of workmen—the cheap automatic-machine attendant and the very highly skilled precision worker required for the tool-shop and for gauge-making.

Thus it is found that in the highly organized and equipped factory there is little requirement for the ordinary type of skilled workman trained on the older workshop methods referred to above. And yet these developments are so recent that thousands of workshops are still of the non-specialized kind, and, including those in which specialization is being introduced with the gradual introduction of modern tools, are still training concurrently with the other two types, the older type of skilled workman accustomed to receive good wages. Thousands of such workmen were, we believe, quite recently available for employment on munitions, if they could be brought into use.

It might here be remarked that in times of peace much can be done by the technical college workshop, with a good representative and modern equipment, to minimize the evil to the workmen arising from a too narrow specialization consequent on these modern changes by the :—

(1) Training of the automatic-tool attendant to become less automatic himself, and to give him instruction in the skilled and more general work of the old English type.

(2) Training of the skilled worker, brought up in the old workshop methods, in the higher work required in setting automatic tools, and where ability is manifest, in still higher precision work, both hand and machine,

At the moment, however, the problem is to utilize this skilled labour, which, like Mahomet's coffin, would appear to be suspended between heaven and earth without visible means of support, in the production of the munitions which are so urgently required. The partial solution which has presented itself to the Authors is not to establish instruction courses for such men, but to find work for some of them on munitions in the lower type of technical college engineering workshop, where they would find the tools with which they are familiar, and in the use of which some of them, at least, are expert. It ought not to be difficult to give out to such workshops work which, owing to its nature or the limited quantities required, is not suitable for the more highly-equipped college workshop on the one hand or for the more cheaply operated labour-saving automatic-tool on the other.

There is next a class of men which should be utilized, and which consists of men with some practical engineering training, but who have for a longer or shorter period been following other types of employment, and have not been in contact with practical mechanical work for some time. Speaking generally, middle-aged or fairly young men who have been through an apprenticeship in the works of a mechanical engineer should be capable of profitable employment on shell-work in a factory. Even if years have elapsed since their contact with practical work, skill gained is never lost, and two or three weeks at a factory should be quite sufficient to enable such men to regain their manipulative skill with ordinary tools, either hand or machine. For such work no special training in the schools ought to be required, nor should the time of the schools be spent on them. Any man classed as a fitter, for instance, who has obtained reasonable proficiency as such, should readily adapt himself in the factory itself to work on a good machine such as a lathe.

Attempts are being made in some places, and are under consideration in others, to give supplementary instruction to selected men of these types, and it has been proposed to extend the facilities whereby such selected men may receive special instruction on modern tools and on modern workshop operations.

The problem of training these men, and the engineers previously referred to, to become efficient on modern high-class precision work is quite a different one, involving psychological problems as well as physical and physiological ones. This has been demonstrated during the past summer, for there have been cases where it has been found impossible to train successfully an otherwise admirable mechanic to be an efficient gauge-maker. The Authors have come to the conclusion that many efficient bench and machine hands cannot be trained to make good precision workers where high accuracy of work at machine or vice is required, say, to the $\frac{1}{10,000}$th of an inch, as in gauge-work. All men have not the delicate touch nor the power to perceive or work to small differences of dimensions. It is, the Authors are convinced, quite as much a question of temperament and mechanical instinct as of training. A careful selection of suitable men for training as precision gauge-makers can only be made by actual trial of individuals under close supervision, and such work should be so arranged as not to retard the output of munitions.

Since the above was written, a scheme has been drawn up for training semi-skilled munitions workers in technical schools. This scheme has been drafted by the Ministry of Munitions in co-operation with the Board of Education, the Scotch Education Department, and the Labour Exchanges. In a memorandum * issued by the Ministry of Munitions special emphasis is laid on the condition that the training to be given must be thoroughly practical and that purely educational ideals must be subordinated to utilitarian methods. Thus there must not be too large a proportion of bench work, which educationally is very valuable, but reducing this to a minimum, the learner, no longer a student in any real sense, must be given as quickly as possible the "machine sense" and preferably be taught to use a definite machine-tool upon which he is likely to be employed, or better still, upon which he has been promised employment, in the factory. In fact, the training, from an educational point of view,

* An abstract of this Memorandum is given in Appendix I (page 748).

is to be pure "cram" work in engineering workshop practice of a strictly limited type.

(iii) *Whether, and under what circumstances, the direct manufacture of Munitions is preferable to training munitions workers.*—One of the most important and urgent problems at the moment is to decide quickly in every case what course to adopt in the very complex conditions revealed in the foregoing sections of this Paper. The first point to settle in each case will be as to whether it is better to arrange for the direct production of munitions or for the training of munitions workers. It is partly with a view to aiding the responsible authorities to decide this important point that much of what immediately precedes has been written, and that full references have been made to the questions involved in the various schemes which have so far emerged for the training of different types of candidates as munitions workers.

In connexion with all such schemes, however, there arises the important and complicated question as to whether it is justifiable to set on one side valuable and specialized machine-tools for instruction purposes, when they are so urgently required for the direct production of munitions. The schemes also involve the absorption of the time of skilled instructors who might otherwise be employed on productive work. There should therefore be seriously considered in connexion with the value of this work—

(*a*) The diversion of large numbers of useful machine-tools and highly-trained mechanics (workshop instructors and teachers) otherwise directly employable in the manufacture of munitions.

(*b*) The proportion of men so trained who afterwards find effective employment on munitions work.

(*c*) The effect on the acceleration or retardation of the production of munitions by the employment of large bodies of short-trained, and therefore only at the best semi-trained, workers.

With regard to (*a*), the diversion referred to leads to reduction of the resources available for the immediate production of the

munitions which are so urgently needed, and the place of this production is to be taken by a production of problematical relative magnitude and importance at some indefinite future time.

With regard to (*b*), the proportion of men specifically trained as munitions workers who may afterwards find effective employment on munitions work will depend upon whether (i) before starting the period of training they had had any previous training in bench or machine-tool work, or (ii) were absolutely untrained except for what little skill they had picked up as amateurs.

Most of the workmen who would come under category (i) have been already dealt with fully in the preceding pages, and the range of possible previous experience is so wide that no general rule can be laid down. But both for them and for the previously unskilled amateur, it is obvious that the chance of obtaining employment must depend on the training given. That training must evidently be very restricted in character, and, before it is entered upon, those responsible for the teaching should have made careful inquiries as to the vacancies likely to be available at its close, and should then direct the teaching strictly to the purpose in view as a piece of "cram" pure and simple.

With regard to (*c*), the conditions are so complicated and various that the Authors at this stage express no opinion, but it has been suggested to them by foremen and works managers that an over-utilization of semi-skilled workers so trained leads to serious damage to machine-tools, requires the constant attention of many skilled men, and may result in a retardation of output. An expression of the expert opinion and of the results of experience by members of this Institution on this important matter would doubtless be of considerable assistance to the Authorities.

3. Other Engineering War Work.

This Paper has already extended to such a length that there is no room to deal adequately with the important work, other than the direct production of munitions and the training of munitions workers, which comes within the purview of the engineering colleges and their equipment, and which has been undertaken by

the colleges. There is, in fact, room for a very full Paper, or even a series of Papers, upon this work alone, but it may be of interest to summarize very briefly the types of work alluded to, which may be tabulated as follows:—

(i) The testing of war materials, for which the splendidly equipped laboratories of first-class technical colleges and technical departments of the Universities are particularly well adapted.

(ii) The testing of new constructional details for military and naval purposes, which can also be well carried out in the same laboratories.

(iii) All kinds of chemical and metallurgical analyses and the analyses of new products for use for warlike purposes.

(iv) The testing of the numerous optical appliances which form so important a feature in modern warfare; also the working out of new designs to meet new requirements, *e.g.*, optical aids for aircraft and anti-aircraft work.

(v) General experimental work of various kinds in connexion with the numerous committees which have been, and are being, organized under the Munitions Inventions Department, the Royal Society, and other public bodies.

(vi) The requisitioning of individual members of the staff to give technical advice on subjects in which these individual members are specialists.

(vii) The training of drafts from the new armies in intensive short courses of special work. Range-finding, field telephony and map-reading may be mentioned as subjects which, amongst others, can be well taken charge of in technical institutes with proper professional guidance. Other subjects will suggest themselves, but, as showing the possibilities, it may be mentioned that nearly 900 men of the Artillery have been passed through such courses at one institution.

The Paper is accompanied by two Appendixes.

APPENDIX I.

Abstract of Memorandum relating to the Scheme for Training Semi-Skilled Munitions-Workers in Technical Schools.

The Ministry of Munitions, acting in co-operation with the Board of Education, the Scotch Education Department, and the Board of Trade Labour Exchanges, calls attention to the following scheme for training men and women in Technical Schools as semi-skilled workers for munitions factories.

Inquiries by the Ministry of Munitions have convinced it that the scheme for training semi-skilled workers in Technical Schools is fundamentally sound, and that where the training has been conducted on the right lines the reports of the Education Officers and employers alike leave no room for doubt as to the value of the training, the adaptability of the learners, and their usefulness in the factories, and the Ministry has decided to encourage the use of facilities for training in all Technical Schools to the full. As in certain Technical Schools machinery and labour have been, and are being, used for munitions making as well as for training, the Ministry desires that preference should be given to the training of munitions workers, except in special cases where very highly-skilled work, such as the making of gauges, is being undertaken.

The scheme gives special emphasis to the importance of the training being of a thoroughly practical character, and purely educational ideals are to give place to utilitarian methods. It is particularly desirable that benchwork, which absorbs so large a proportion of the learner's time in Technical Schools, should be reduced to a minimum, and the aim of all such courses should be to impart to the learner the "machine sense" and to teach him to use a certain definite machine-tool on which he is likely to be employed in a munitions factory. To this end, it is desired that the Technical School Authorities should get personally into touch with munitions works so as to direct the tuition on suitable lines.

For the purpose of drawing up a Training Scheme where none is in operation, a small local Training Committee should be formed to assist the local Education Authority and the Managers of the school or schools concerned. It will be the duty of this Committee to draw up a complete statement of the scheme, giving all details of machinery available, staff, number of learners, etc. The Ministry does not propose to insist upon absolute uniformity in detail for all Training Classes, but the following points are to be carefully noted * :—

(1) No male learner must be accepted who is of military age, unless he is for some reason debarred from Military Service.

(2) As far as possible, learners should be men or women of superior intelligence who are likely to learn quickly —for example, professional men, those who have had a secondary education, men skilled in other trades, such as cabinet-makers, jewellers, etc., who will return to their ordinary occupations after the war.

(3) Preference should be given in the first instance to those who are willing to leave the town where they live and go where there is demand for labour.

(4) Each learner entering a class must give a written undertaking that he will work whole-time in a munitions factory on the completion of his course. If he fails to do this without good cause, the cost of the training will be recoverable.

(5) No fee should be charged for any course in respect of which it is intended to claim a grant from the Ministry of Munitions.

(6) Each learner satisfying the Head of the School should, on the completion of his course, receive a certificate

* The numbered and lettered paragraphs which follow are verbatim quotations from the Memorandum.

of efficiency specifying the nature and duration of the course. The utmost care should be exercised in this matter. The whole scheme will fail if incompetent persons are placed in factories on the strength of their certificates.

(7) The Head of the School must have absolute power, on the advice of his Instructors, to eliminate the unfit at any stage of the training. This power must be fully used if waste of time and money is to be avoided.

(8) Weekly returns must be made in duplicate to the Ministry of Munitions for their use and that of the Board of Education (or the Scotch Education Department) on the lines of form annexed.

(9) Periodical inspection of Training Classes will be undertaken by the Board of Education Inspectors and representatives of the Ministry of Munitions.

(10) It will probably be found that the number of applicants will be far in excess of the accommodation available and that a waiting list will be necessary. It is not essential that learners should be taken strictly in the order of their application. Priority should be given to applicants who seem likely to make specially good munitions workers.

(11) The length of the course must be largely conditioned by consideration of local circumstances. The Ministry is not prepared to sanction any course which provides less than 30 or more than 100 hours' instruction. It is suggested, too, that in all cases where classes are worked in shifts, arrangements should be made that no course should last for more than one month.

The financial arrangements made between the Ministry of Munitions, the Board of Education, the Scotch Education Department and the Treasury allow for the payment by the Minister of :—

(A) Salaries and fees of teachers or a proportion of these, according to the time devoted to the work.

(B) Actual cost of fuel, light, cleaning and materials so far as not supplied by the Ministry of Munitions.

(C) Cost of making good any damage to premises, equipment or apparatus.

(D) A reasonable allowance for depreciation of apparatus.

(E) The cost of altering, providing or re-assembling machinery to meet the special requirements of the Ministry of Munitions.

The members of the Training Committee are to leave nothing undone to ensure the placing of students in munitions factories.

Normally the output of the Technical Schools is to be absorbed in local factories, but cases will occur where local openings are not immediately available, and it is suggested that preference should be given to applicants who are ready to work anywhere. In such circumstances, the machinery of the Labour Exchanges should be of assistance.

Where there are Technical Schools in non-industrial centres with adequate equipment for training, it may probably be found that there will be a considerable number of applicants willing to work elsewhere after training, in which case transference of labour can be effected through the Labour Exchange. If an adequate supply of such applicants is not forthcoming, the Ministry of Munitions and the Board of Education would favour the temporary removal of machinery to training centres where there is a demand for labour and facilities.

It is to be understood that all these proposals apply to the training of women as well as of men, but the Ministry is not in a position to decide in what proportion women should be accepted as learners in particular centres; this must be left to the discretion of the local Training Committee. The Ministry emphasizes the necessity of getting assurances of employment for women before undertaking to train them.

The "trained workers" will not be skilled engineers. At most they will be semi-skilled workers, but having had on an average 60 or 70 hours' practice on lathes or the like, they should be more useful recruits in a shell factory than those who have never seen a lathe before. "The Ministry is convinced that the scheme will help in some degree to provide the labour which will be urgently required, and that it needs only a careful attention to local conditions and the cordial co-operation of the various Authorities to make it a success."

APPENDIX II.

Technical Colleges and the War.

Schedules of Information Regarding Present and Possible Work.

1. *Manufacture of Munitions.*

(i) Date of commencing.

(ii) Whether the work is done for a Government Department, or through the local Munitions Committee, or in orders received from a company or private firm.

(iii) Conditions of payment for munitions work with respect to costs of material, direct labour, shop charges (and profit, if any).

(iv) Kind of work manufactured, and whether finished work or partly finished work.

(v) Number of hours per week, and number of shifts if more than one, with weekly hours per shift.

(vi) Whether the work undertaken is under the direction of the engineering staff or under some outside firm or committee.

(vii) Extent to which the engineering staff is employed in this work and simultaneously (if at all) on educational work.

(viii) Extent to which engineering students, day or evening, are employed.

(ix) Extent to which outside or additional workmen are employed.

(x) The extent to which the additional assistance is (*a*) unskilled, (*b*) semi-skilled, or (*c*) highly skilled.

(xi) Rates of wages to (*a*) staff, (*b*) students, and (*c*) others.

(xii) The extent to which staff wages or salaries are charged directly to munitions account (*see also* (iii) *above*).

(xiii) Holidays and overtime worked on munitions and payment for same.

(xiv) If not already engaged in the manufacture of munitions, is it proposed to undertake such work?

2. *Non-educational War Work.*

(*a*) *Testing of Materials for Munitions or for Tools and Ancillary Apparatus used in the Manufacture of Munitions.*

(i) Actual testing undertaken arranged, if necessary, in different classes.

(ii) For whom the tests were made.

(iii) Approximate quantity of material tested.

(iv) Equipment available for each class of testing undertaken.

(v) Staff and skilled assistants available.

(vi) Method of payment (if any) as regards:—

(*a*) Out-of-pocket expenses.

(*b*) Other remuneration, and by whom made.

(vii) Particulars of other tests which can be undertaken, with data regarding staff and equipment available.

(*b*) *Testing of New Constructional Details for Military and Naval Purposes.*

Details as under (*a*) (i)–(vii), but quite general as regards (i), so as not to disclose confidential matters.

(c) *Analyses, Chemical and Metallurgical.*

Details as under (*a*) (i)–(vii), *mutatis mutandis* with the proviso as under (*b*).

(d) *Testing of Optical Appliances.*

Details as under (*a*) (i)–(vii), *mutatis mutandis* with the proviso as under (*b*).

(e) *Particulars of Research and Experimental Work Generally for the Munitions Inventions Department and Official Committees of all kinds.*

(i) This can only be stated quite generally, as much of the work is, and must be, confidential, and so diverse that no one schedule can be applicable.

(ii) Special mention, giving full particulars, should be made of any staff and equipment available for work of this kind likely to be of service to the country and not yet utilized.

(*f*) *Personnel for Other Work.*

(i) Particulars of staff and students who have been engaged as workmen or in other capacities with Government Departments or private firms for the manufacture of munitions or other purposes

(ii) Conditions of transfer.

3. *Educational War Work.*

(*a*) *Training of Munitions Workers.*

(i) Date or dates of starting the courses.

(ii) Duration of courses and number and duration of lessons.

(iii) Kind of training and brief outline of syllabus.

(iv) Extent to which training is being given to prospective munitions workers other than in the direct manufacture of munitions.

(v) Particulars of supplementary training (if any) given to skilled hands.

(vi) Particulars of training (if any) given to women.

(vii) Fees (if any) charged for instruction.

(viii) Whether the instruction or supplementary training has been given by the engineering staff
and/or under any outside firm or committee.

(ix) Total number of hands enrolled.

(x) Method of selection, especially as to the extent to which previous workshop experience was made a condition of admission, or not insisted upon.

(xi) Number of previously unskilled hands who have received instruction.

(xii) Number of semi-skilled hands who have received instruction.

(xiii) Number of skilled hands, according to Trade Union standards, who have received the supplementary training offered.

(xiv) Number of women enrolled.

(xv) Number of those enrolled who have taken full advantage of the instruction available.

(xvi) Number of those enrolled who have not taken efficient advantage of facilities offered.

(xvii) Obligation (if any) to find employment for hands trained in the courses.

(xviii) Proportion of hands trained who have been given work in munitions factories.

(xix) General remarks on the results of training of youths and men (unskilled, semi-skilled, or skilled according to Trade Union standards).

(xx) General remarks on the results of the training of women, or on their ability, or otherwise, to stand the strain of work under factory conditions.

(*b*) *Other Educational Work.*

(1) Particulars of courses and classes for officers, N.C.O.'s and privates, or others serving with the colours.

(i) A brief syllabus of the courses and classes.

(ii) Duration and number of class hours of the courses and classes.

(iii) Whether the teaching was given by the regular staff of the institution, or by the staff assisted by special teachers, and the proportion of the work undertaken by such special teachers.

(iv) Type of students enrolled.

(v) Number of students enrolled.

(vi) Fees or other remuneration received and by whom paid.

(vii) Board of Education grants (if any) received.

(viii) General results obtained

(2) Similar particulars of other courses or classes (if any) directly bearing on war service.

4. *Suggestions for Additional Work.*

The above schedule is necessarily not exhaustive, especially as regards the type of war work which may be undertaken by Technical Colleges. Suggestions for work not referred to are therefore desirable.

Discussion.

The PRESIDENT said that before the Paper was read he desired to call attention to the following Resolution, which had been received from the Ministry of Munitions, which seemed to him to be of importance: "The Minister of Munitions appeals therefore to those responsible not to make public the position of works other than those already known as munitions factories now engaged in the manufacture of guns, munitions, explosives or other things, or to make statements calculated to show directly or indirectly the scope of the Government work on which they may be engaged, or the quantities which they may be able to produce." The Government was afraid of information in regard to the production of munitions being so used as to help our enemies, and possibly to guide them to seek out those places which it might be most important to destroy.

(The President.)

He appealed, therefore, to the Authors, to the Members, and to the gentlemen of the Press to make a special note of the Resolution. He thought it would be necessary for the Institution to edit the Paper before it went into the Journal, in order that any mention of localities or other things, which contravened that expression of opinion by the Ministry of Munitions, might be erased. Neither localities nor quantities being produced or capable of being produced in particular places ought to be mentioned. With that caution, he had very much pleasure in asking Dr. Walmsley to read the Paper which he and Mr. Larard had prepared.

The Paper having been read in abstract by Dr. Walmsley—

The President said he was very glad indeed to find that the change in the hour at which the Meetings of the Institution were held had not prevented an excellent number assembling to hear the very interesting Paper that had been read. He would not take up the time of the Meeting by any criticism of his own, because he knew there were many present who wished to speak on the subject. There were, however, many points in the Paper on which, as an old teacher, he held some opinions. It was a revelation to him that a great deal of the work which engineers considered to be skilled work could now be undertaken, after a comparatively very small amount of training, by unskilled workers or by women. It was really wonderful to see a line of lathes worked entirely by women in their tidy overalls and mob caps, turning 3-inch and 3½-inch shells with very slight male assistance. He had great pleasure in proposing that a hearty vote of thanks be accorded to the Authors for their interesting Paper.

The Resolution of Thanks was carried with acclamation.

Dr. R. M. Walmsley, after thanking the members very cordially indeed on behalf of his colleague and himself for the hearty manner in which the vote of thanks had been adopted, said the Authors knew that the Paper was full of controversial matter.

They had given their own opinions and expected that they would probably be very much attacked. They knew they were not upon scientific physical grounds where measurement finally settled the question.

Mr. J. D. Armstrong (of Leeds) opened the Discussion.

Dr. William Garnett said he was glad to have had the opportunity of listening to the Paper, because it would be difficult to find two Authors more competent to deal with the manufacturing and teaching sides of the munitions problem as presented in educational institutions. Coming face to face, as the country had recently done, with the production of highly specialized work, it had been learned that in some measure the engineering schools required development, and that they must not be content in future with training the fitter and turner of thirty years ago. In the historical perspective which the Authors had drawn, the methods of Boulton and Watt and those of Whitworth were blended in the far distance, and the range-finders of the Authors failed to detect the difference of parallax. He was not prepared to accept so near a vanishing point, for he was brought up to regard the Whitworth system as something like the acme of engineering accuracy. But since those days the milling machine, the universal grinder, and other tools of precision, the capstan, a whole battery of automatic tools and limit gauges, had come, and come to stay until they were replaced by tools of still greater accuracy and capacity, and students must be trained to work to the degree of accuracy now demanded by standard gauges and interchangeable parts.

The mechanical training of students must be developed in two respects: the first was the use of precision tools, and the second was tool-making and tool-setting. He did not think much could be done with the automatic tool, properly so-called, in the schools. It was too productive and too highly specialized; but the capstan lathe might quite suitably be introduced for the purpose of teaching tool-setting. Automatic tools were frequently so unique that it was necessary to learn separately tool-setting for the tools

(Dr. William Garnett.)

of each maker. Formal training, as the educationalists called it, would not suffice, because there was not enough "transfer" from one tool to the other. When a capstan lathe was employed for training in tool-setting and, incidentally, in tool-making, it was practically outside the productive field, for as soon as the tools were ground and set so as to produce a perfect piece of work, the time had come for taking them out and starting afresh with a new set of tools or a new pupil. There could be no doubt that in normal times tools of that description should find a place in all engineering schools of the first rank, but the question might well be raised whether at the present time it was justifiable to transfer tools of such capacity from production to education. The answer to that question depended on whether workers were wanting tools or tools were wanting workers. In the latter case it might be worth while to bring a capstan lathe out of the works and into the school for a couple of months, if thereby a hundred capstan lathes could be provided with tool-setters, and it might even be worth while to make the transfer merely to give a dozen turners some practice in using the capstan lathe under supervision.

Some time ago he (Dr. Garnett) paid a visit to a private works engaged on munitions where the management was so keen on securing half-skilled workers with some experience of the semi-automatic tool that he was offered the free loan of a new capstan lathe if it could be employed for that work; and he had since seen larger and more specialized tools similarly lent to a school by more than one munitions company in order that men might be trained to use them for the special operation for which they were designed. The action of those companies, which presumably knew their business, indicated that there were circumstances under which it was worth while to appropriate, for a time, highly productive tools for the sole purpose of training, even in the present times of pressure. A time seemed to be rapidly approaching when, for the ordinary work of the shops, there would be a demand for only two types of workers—the highly-skilled tool-maker, tool-setter and precision worker, who was quite at home with $\frac{1}{10,000}$ inch, and the unskilled tool-minder, who could learn his job in an hour or two

in the shops, but was nevertheless all the better for some preliminary training in vice and lathe work. That time had not yet fully come even in munitions work, for in many, though not all, munitions shops there was a demand at the present day for plain turners, and tools could be used profitably in the hands of semi-skilled workers at low wages for work for which very different tools would be employed under normal conditions. Nevertheless, the most striking feature of the present labour market was the large number of men who, a few years ago, would have passed as skilled fitters and turners, who were now unable to obtain employment at ordinary trade wages.

When the war was over, it would be necessary to aim at securing in the schools a higher degree of accuracy than that which had hitherto been attained. At present it was rare to see a universal grinder, while universal milling machines were not plentiful in an engineering school; and where precision tools were to be found, they were vastly outnumbered by the ordinary lathes and shaping machines of thirty years ago, at any rate in London. That distribution of tools had introduced some difficulty into the problem of gauge-making in the colleges and polytechnics. In the majority of cases the roughing-out operations took far less time than the finishing, but the ordinary engineering school would boast a dozen tools suitable for the former against one adapted to the latter class of work. When a large number of gauges had to be made, each requiring a dozen operations, the tools, like the men, engaged in each operation must be proportioned in number to the time required for that operation if tools and men were to be kept fully employed.

The extent to which teaching could be advantageously combined with production in the engineering schools in the present time of stress had not been definitely determined. The distribution had settled itself for better or worse more or less permanently in London, and the institutions possessing well-equipped shops with, say, a couple of dozen machine-tools, had been used almost exclusively for production, and in some cases extra tools had been transferred from smaller institutions to those workshops where

(Dr. William Garnett.)
room existed. On the other hand, the lathes, drills and vices belonging to the manual training centres of the Elementary School system, which formed units too small for economic supervision, had been concentrated for the most part in two institutions which had been used almost exclusively for teaching purposes. In one of those institutions countershafts had been erected for all the treadle lathes brought from the centres. In the others a fast-and-loose pulley had been placed on the crank-shaft at the end remote from the fly-wheel, avoiding the necessity for separate countershafts, with the inconvenience only of introducing more moment of inertia into the system than might, *a priori*, be thought desirable.

The Authors had asked about the results of that teaching work. He was not at liberty to state precisely where and in what work the students had found employment. The great majority on joining the classes had had no experience of engineering work. They included professional men of many sorts, clerks and other commercial men, and skilled tradesmen belonging to the building and other trades. The course extended over six weeks, and included 144 hours of actual work. The jobs were a series of graded exercises of the type well known to manual training instructors, but towards the end of the course the better students might be entrusted with the carrying out of some useful work, such as the turning of test-pieces to gauge. Of 518 workers who had completed the course of instruction in one school, 357 had been placed in Government or in private munitions works. Many were employed on capstan and turret lathes, many more on plain turning, and one at least had gone as a gauge-maker for cylindrical gauges. It would be noted that in the school to which he had referred, the course of instruction extended over 144 hours. The Board of Education suggested a period not under 30 and not over 100 hours. In those provincial institutions in which the course had been reduced to 10 hours, no pretence had been made at a course of training. The 10 hours had served simply to introduce the pupil, if a novice, to the workshop atmosphere, aptly expressed by a former Professor of Engineering as "teaching him how to

pinch a spanner from the next man without being seen," and for the purpose of a test, enabling the school authorities to observe how the pupil shaped, and then to be in a position to recommend him to would-be employers as first, second, or third class. But even where the training extended to 100 hours or more, the most that could be done with the novice was to teach him to perform certain operations, in the hope that if he were young he might, when the war was over, study engineering. When he (Dr. Garnett) was asked some months ago what course he would recommend for these workers, he said that he would throw overboard all the principles he advocated before the war, as the business now must be production and not education.

The Authors had referred to the difficulty of suitably hardening the gauges in the workshops of technical institutions. He took up that subject some months ago, and recommended that all the gauges made in the polytechnics and technical institutes in London should be hardened in, say, two institutions where electric muffles should be maintained at a temperature of 750° C., or a little higher, and reduced to that temperature when the gauges had been sufficiently tested, and all the hardening should be carried out by workers devoting themselves exclusively to it when required. He found, however, that when he made this suggestion he was met with the reply that a gas blowpipe, a cherry red, and a practical operator were all that could be required.

Although repetition work loomed very largely in the manufacture of munitions, the speaker did not intend to imply that the time would ever come when there would be no room for the ordinary "fitter and turner" in many branches of engineering, especially in general engineering and repairs work. He was sufficiently old-fashioned in his ideas to think that a boy could learn very much of the nature of the materials on which he was working, by using hand-tools and a foot lathe for a few months. By these means he made friends with his material in a manner which was impossible when his cutting tool was fixed and his lathe was "power driven." But these were points for consideration in times of peace only.

Mr. H. G. Taylor said that the Paper opened out a very considerable range of inquiry, and afforded an ample ground for discussion. It was quite impossible in a Paper of this description to escape from the educational aspect of engineering. He was tempted to devote some time to that portion of the subject, but he quite recognized that at the present moment the members were assembled to discuss what were the best methods by which either the regular students of the colleges or the incoming students of the colleges could be taught to become useful in as short a time as possible. Since the beginning of last July he had been in charge of classes for the training of munitions workers, and during that time he had learned a great deal about human nature, because he had come into contact with people of so many different classes. Every imaginable profession and calling had come under his view, from parsons and gardeners to journalists and omnibus-drivers, and in most cases he had been able to turn them out successfully. So far, he knew as a fact that at least 90 per cent. of the men who had been trained had become satisfactorily established in munitions factories, and many of them were doing remarkably well.

There was one feature of the work, from an educational aspect, on which they particulary prided themselves. At the very outset of the training scheme they were approached on the question of the advisability of training tool-setters, and inquiries were made if it would be possible for them to do so. They possessed no up-to-date automatic machines, but only the ordinary lathes, milling machines, etc. At first it appeared impossible to do much in tool-setting at the College. On further consideration, however, he thought that something might be done in regard to the training of tool-setters. He approached a firm which particularly wanted such men, and requested that the men should be put through the course of exercises, and that the best of them should then be sent to the works in order that they might be practically tested. A recognized course, therefore, was established, consisting of about 140 hours' work. On the average, seven students were allotted to each instructor. The instructors were not merely college teachers, but were skilled men who had done the

work themselves. Every student had to do his share of hardening, tempering, drilling, tapping, machine-planing, slotting, milling, the usual screw-cutting on the lathe, V threads, left-hand square threads, and inside threads, and all that work was taught in four weeks.

Mr. Larard asked if those men had had any previous works' training.

Mr. Taylor said they had not, in the great majority of cases, and in the case of those turned out as tool-setters, not one had served an apprenticeship. After the course, the men were sent down to the works he had mentioned, where they received, at the most, one month's training, and were found so satisfactory that a request was received by the College that more men should be sent. Of the output of the College, quite one-fifth had gone to that particular works, and they were all doing very well, not one having proved unsatisfactory. It was his good fortune on the previous Tuesday to visit those works, and, as the College had not any of the automatic machines on to which the men were put when they went to the works, he thought it would be advantageous if he could get some. The manager informed him that the men who had been sent down from the College were doing remarkably well, and that some of them had already arrived at such an advanced state that they were training the incoming probationary tool-setters. The men, therefore, had not only become skilled tool-setters themselves, but were super-skilled, and were able to teach learners. As examples of the type of men, it might be mentioned that the selection comprised, amongst others, a solicitor, journalist, house agent, art student, day school teacher, wounded (regular) soldier. He had a conversation with the manager with reference to supplying the College with automatic machines, and the manager told him that if it was feasible he would do so, but personally the manager thought the College could not do better than follow its present procedure of putting men through their ordinary course, teaching them their alphabet, so to speak, and when they

(Mr. H. G. Taylor.)

were sent to the works, they would be taught to spell. After carefully thinking the matter over, he had come to the conclusion that that was the best thing to do, and that the College did not require any automatic machines. He did not at all admit the educational value of a capstan lathe, an automatic milling machine, or tools of that kind.

He thought engineers had become rather confused at the present time with reference to the meaning of the term "highly skilled." A man who could set up an Auto-Lincoln was not necessarily highly skilled; he was highly specialized. It was a fact that men, such as turners and fitters, had been taken from other departments and put under training as tool-setters, but in most instances this had proved a failure. The works preferred the men who came from the University, as these had been trained on a machine with one cutting tool. When they approached a machine cutting with six tools at once, they were not embarrassed, but accepted the fact. On the other hand, when men, known as skilled, were shown such a lathe, they looked at it and did not believe it; they simply refused to accept facts.

As regards mechanics who had left the trade a number of years ago, he had not found them of the type he could recommend as tool-setters. The College thought it was doing the best thing by putting the men to whom he had referred through their paces, giving them a strictly limited, but real, education—no specializing —until they had gone through all the preliminaries he had mentioned, and then putting them on to manufacture. He thought it would be of interest if he gave a rough sketch of the Course that was given, because it might be helpful to other people who had charge of munitions classes.

The following illustrates the Course:—

FIG. 1.—Flat gauge in wrought-iron, made correct to $\frac{1}{1000}$ inch.

FIG. 2.—Tool-steel gauges, introducing the idea of limit gauges. Hardened and tempered and afterwards finished to size.

FIG. 3.—Cast-iron girder embracing the following exercises:—

Slotting.—Three key-slots A B C; afterwards plain slotting the intervening portion to the line XY.

Shaping.—Portions D and E removed to the level of the line XY. Vertical face F cleaned up.

Drilling and Tapping.—Six holes drilled in web in three sizes, clear and tapping. Three holes tapped out.

Hand-Screwing.—Three simple plugs chased with dies to fit the three tapped holes.

Planing.—The four edges G planed and made to size.

Milling.—The underface faced to the line H and afterwards slotted the whole length as K.

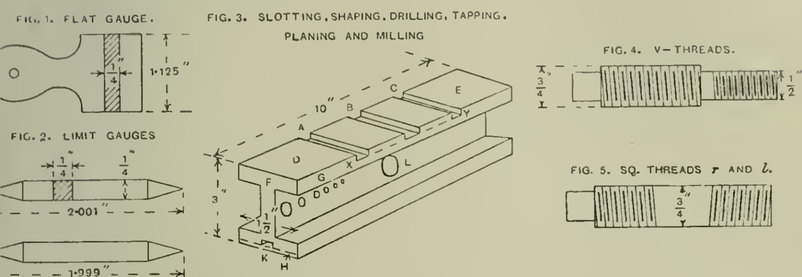

Fig. 4.—Plain cylinder turned and screwed as shown. Whitworth V-threads.

Fig. 5.—Plain cylinder turned and screwed right and left hand square threads, 5 per inch. Students work out and set up the change-wheels in all cases.

In Fig. 3 a central hole L is bored in the lathe and afterwards screwed to fit the square thread of Fig. 5.

On the hand-shaping machine a simple cube is made. All the students are encouraged to forge and harden their own tools, and each receives special instruction on the use of the micrometer and vernier.

Mr. A. Wigglesworth said he had listened to the Paper with the greatest pleasure, because, as Dr. Walmsley had said, it opened a vast field for discussion, and he thought the discussion which had so far ensued was quite worthy of the high class of the Paper itself. As the most intimate subject in connexion with the war was the output of shells, he desired to confine his remarks to the training of men for that purpose. The criticism which had been brought before him in many of the factories, where trained students

(Mr. A. Wigglesworth.)
had been sent, was that the general knowledge which they had acquired in six weeks was of necessity somewhat superficial, and did not enable them to start in the factory with that knowledge of the work which they really ought to have, if they were to assist the management in obtaining a quicker and better output from those particular men. That being the case, he thought it remained to be considered how best to train the men for that particular work, because he thought every engineer present would admit that a general training in six weeks was entirely out of the question, and that the men could only do the simplest operations. If, then, the technical schools were to train those men to a single operation which was to correspond with the operation they would carry out in the factory, he believed the purpose of the Ministry of Munitions in issuing the circular which was referred to in the Paper would have been carried out. But if that were not done, the purpose would not have been carried out, because the men who had received training in all the various things which had been mentioned in the course of the discussion would be of very little more use in the factories than men who were taken right out of the labour market without any previous experience.

It had been brought to his notice also that the students, when they went to the factories, had the notion that they had acquired a considerable degree of skill. That was a very dangerous idea, because they were more difficult to teach than men who went openly with a blank mind saying that they knew nothing, and who started unprejudiced. As each manager and often each foreman had his own particular methods, those men were soon able to acquire the necessary knowledge and did not have to unlearn what they had previously learned. If the output of shells was to be the chief consideration in the training at the colleges, he strongly urged that the training should be confined as far as possible to a single operation. He was sorry to disagree with the last speaker in that respect. He suggested that the capstan-lathe should be introduced as much as possible, and that all idea of training by means of an engineering course should be abandoned for the time. It was a well-known fact that thousands of workers were required

for the factories, and if that particular class of training would fit the men to go into the factories and, with a minimum amount of scrap, turn out really good work which could be passed by the authorities at Woolwich, he thought the training would be successful. It was only four months and a half since the movement was started, and already quite a substantial number of students—about a thousand—had been trained, which gave an idea that the work had been satisfactory.

The only other point to which he wished to allude was that of the management. He thought he had never investigated any subject in connexion with which he had heard such a vast difference of opinion as to the capabilities of the students. He had heard them described, so far as the results they had turned out were concerned, as wonderful; on the other hand, he had heard them described as total failures. He thought it all depended upon the point of view of the management, and their ability to apply the particular training the men had received to the best advantage. It would, of course, be of great advantage if there was a closer correspondence between the managers of the different factories and the technical colleges. For instance, if a factory in a certain district knew it was going to receive men from a college, it would be of great value if the management were to meet occasionally to ascertain what class of workers was required, and, if possible, to train the men in that particular work. As an instance, he mentioned the case of an important provincial town which he thought was perhaps the best example of successful training for a specific purpose. A great deal of the credit for that good result was due to the manager of the Labour Exchange, who had a good practical knowledge of his business, and, being well in with the different factories, had called on the managers and found out what they really wanted. He did not think there was a single training centre where students had been drafted into the factories with less trouble. There had been no loafing about or waiting to get a place. The moment they were trained, and the manager knew they were suitable for the work, the men were sent straight to the different factories and started work the next day after they left the college.

Professor G. J. Wells said there was one general remark he was tempted to make on the subject dealt with in the Paper, namely, the criticism of the conflict or the supposed conflict between "Professors" and the "Shop." The statement was made in the Paper: "Many practical engineers and some engineering professors have in the past looked with disfavour, almost with contempt, on the college workshop, and have doubted whether any serious work or instruction of real value can be given in it from a practical engineering point of view." He thought a large part of that difficulty was due to the various Committees, because, if the authorities required their teachers to have high academical qualifications, it was unreasonable to suppose such men also could have adequate workshop training. It seemed to him that if the authorities had in the first instance recognized the need of teaching actual engineering, the possibility of conflict between the two would have been avoided. An engineer only could teach engineering of real value. The remark was made in the Paper that the Authors thought the educational authorities should take charge of the proposed centralization. Personally, as the result of his experience during the present crisis, he thought that much time and money would have been saved, and an increased output obtained, if all such work in the future were taken sole charge of by engineers. There was no body of men better qualified for that purpose by their training than engineers, and he was sure that would be admitted by every member of the Institution who had had to do actual manufacturing work.

The work being carried on at the College with which he was connected had come before him in the following way. Early in the war the question was raised as to what that College could do. There were two possible courses open, first, to train munitions workers, and, secondly, to send the skilled workers they possessed to a suitable place where their special skill could be utilized. The Government decided that the latter course should be adopted, and as a result the College lost at an early stage the whole of its trained skilled workers. The next step in the process arose because it was thought that the College could do something mired

and, as the Paper suggested, they took up testing. As a result, a large number not only of physical but commercial tests were being carried out, and the electrical engineering, physical, and mathematical departments had been exceedingly busy in that direction. That part of the field was now fairly well covered.

Then the next question that arose was that, as the College possessed some of the antiquated tools to which reference had been made, which ought to be capable of being used, it was necessary to decide the sort of course which would be best fitted to utilize them advantageously. He was able to say that the line of work, first suggested some three or four months ago, had been proved to be quite correct, and it was gratifying to find that those who had taken part in the discussion were entirely in agreement with what was now being done. A course was started which consisted of a good many exercises and similar work, but it was at once obvious that what was required was not men that were "neither fish, flesh nor fowl, nor good red herring," but men who could do munitions work in the local shops. The College had got into contact with the local Committee of Munitions and ascertained from them the exact quality and kind of work that was going on in the district around them. Having discovered that, they tried to find the right material in the shape of men to carry out that work, and to a very large extent they had been successful, not only in placing the men they trained, but in having further demands made upon them for supplying additional men. Scarcely a day passed but an application was received for a turner or a man capable of doing some other kind of work, the request being accompanied by the statement that a man should be sent like one who had been supplied before. All that was exceedingly satisfactory, but it had only been achieved by throwing overboard all the educational routine of graduated exercises and the like, and trying to make the men fit to do the work on which they would be actually engaged.

One of the latest developments was in regard to shell-turning. the College discovered that a good many shells were being turned difhe neighbourhood, and, owing to that fact, they were able to th

obtain a supply of the ends of the bars of steel that were actually used in the shops. As everyone knew, in shell-making there was always some material over, too short to work up, and that spare material was now utilized in the College. It was first centred, then put into the lathe, and a $4\frac{1}{2}$-inch shell prepared. The groove was turned and the base prepared for the end plates. An attempt was being made to do the "waving" in the grooving by means of a special tool. Then it was turned round and the nosing done; next, the inside was bored out, but they always made a point of boring the inside too small, because that allowed them to utilize the stuff that was over for two shells, and so enabled the men to repeat the process of turning and cutting the driving groove, etc., without waste of good material. He had also been able successfully to place several men for turning shell-punches.

He was originally of opinion that the jobs to which he had referred could not be done by the class of men turned out, with the short training they received, with a sufficient degree of accuracy, but he was bound to say that the proof of this had shown that he was wrong in his estimation of the amount of skill that could be imparted in so short a space of time. Lastly, they had trained men as far as they could in the limited time available for accurate work, and, to discover their amount of success, they make a definite test, which the Authors called a "precision test"—that is, to find the ability of the men to "feel," because, after all, that was what was really wanted. First, the man had to be trained to feel whether, when he was callipering, the article was $\frac{1}{1,000}$, or $\frac{2}{1,000}$, or $\frac{1}{10,000}$ tight. Secondly, he had to learn to feel the depth of cut of the tool, in order to give him some idea of whether the chip he was cutting off was the proper size. Most of the limit gauges that had been produced were very close; they were very nearly accurate, the usual fault being slight tapering. He would like to know from the Authors whether they knew the proportion of wasters in some of the other centres.

It was not easy to speak at present of the exact value of these trained men; several instances of real success had come to the knowledge of the speaker, but there were several cases where fair

treatment had not been given to the munitions trained man. One instance would illustrate this point. A man had been recommended as one who would, if some opportunity were given, do good work as a turner on straightforward work. At first when in the shop he experienced difficulty in getting work; eventually he had to make his own tools before starting at a lathe. He had also to make some dies for screw-cutting, and seemed generally set to do work such as demanded the skill of a tool-maker, instead of being set some job that such a man might reasonably be expected to do. Nearly all the disappointments met with would be, he believed, eventually traced to the "duty" that led the skilled worker to see that these raw hands were rejected as incompetent sooner or later. From the start the closest touch had been maintained between the College, the local Munitions Committee, and the Board of Trade Labour Exchange.

As regards organization, etc., every effort was made to show the men being trained what would be required of them when at work under commercial conditions, but as the Authors said, educational and commercial conditions could not be easily reconciled under the same roof, and so far, in the matter of "training" the men at the speaker's College, no pretence was made to do so under the commercial conditions that existed in a shop. In this matter no pretence was made as regards booking the time spent upon any piece of work, whilst the College staff had been so much reduced that no use could be made of the data until after the War, when its value would be very questionable, except for statistics. The Authors were to be congratulated upon having been able to find the time required to put this Paper together, whilst it appeared to be marvellous that they should also have been able to carry out a complete prime cost system.

Mr. C. E. Larard, in reply, said he could add very little in the short time remaining for the discussion, but he would supplement his remarks in the joint Communication which the Authors would send in for publication in the Proceedings. The chief objects of the Authors in writing and presenting the Paper to the Institution were to enable a discussion to take place on matters of very vital importance,

(Mr. C. E. Larard.)
and at the same time to show what was being done and what could be done in the technical colleges to assist the country during the present national crisis. Those objects had been achieved, and if they were to spend a good deal of time in adding to the facts which were embodied in the Paper, he did not know that they could say very much more. The President had made one remark which must have struck all practical engineers as being exceedingly apt, when he called attention to the remarkable revelation which had been brought about by the utilization of unskilled and partly skilled labour in munitions factories, particularly in relation to women. He thought that must have been a revelation to all the members, particularly to old engineers who had gone through the usual process of serving an apprenticeship and picking up their skill and knowledge in the ordinary way.

He considered that the remarks made by Dr. Garnett, Mr. Armstrong, and Mr. Wigglesworth were exceedingly valuable, and the points they had brought out clearly deserved very special emphasis. Mr. Wigglesworth, for instance, made a remark to the effect that general training at the present time was entirely out of the question. He quite agreed with that statement. What was wanted in connexion with unskilled labour was, as Mr. Wigglesworth said, to train the worker to one simple operation, but in the technical colleges the students and other workers were able to do, and would be able to do in the future, more than one operation. Mr. Taylor had outlined a course of simple instructional work, but personally he very much doubted whether that instructional work could be of any real value in a munitions factory. No man with the short training referred to could possibly apply that sort of exercise work to munitions work of practical importance.

Mr. Armstrong had called attention to articles which could be manufactured by labour which initially was entirely unskilled, but which had been taught to be skilled in the particular operation in a very short time. That was common knowledge to the engineer. A boy fresh from school could be taken and put on a capstan-lathe, and in a fortnight to a month he could be earning 15*s.* a week at piece-work. He would probably be rated at 4*s.* to 5*s.* a week.

Reference had been made in the Paper to combined teaching and manufacturing, and he understood Dr. Garnett to remark that that could be done effectively; but personally he held a totally different opinion, having had experience in connexion with both. It had been shown that if a shop were organized for munitions work for one part of the day and then a body of unskilled men were, later in the day, allowed to use the same tools for instructional purposes, a good deal of upsetting of work was caused; lathe centres and tools were damaged, and it was necessary to spend hours the next day in putting the tools right and resetting the work before the munitions work could be gone on with. If the tools could be kept separate and distinct, one set being kept for the munitions workers and another for training the munitions workers, the scheme was more feasible, if the other difficulties could be overcome.

Dr. Garnett said that he did not say in his remarks that teaching and manufacturing could be combined effectively.

Mr. Larard regretted that he had misunderstood Dr. Garnett's remarks. Mr. Wigglesworth had referred to the various opinions which had been given by different individuals on the ability of engineering students or students in the works; some had thought they were wonderful, and others had thought they were total failures. Mr. Wigglesworth had further stated that the value of the training must be in its application and in the ability to know exactly how to utilize it. He fully agreed with Mr. Wigglesworth in that respect. In his own experience, engineering students with no previous works' training had in two or three months been able to finish gauges accurately to $\frac{1}{10,000}$ inch, but those students, as pointed out by the Authors, were comparatively few in number. They had to be selected students, but such students could be very quickly trained to gauge-making.

He thought Professor Wells had misunderstood one remark in the Paper. Professor Wells presumed that the Authors recommended that centralization schemes should be carried out and the engineering

(Mr. C. E. Larard.)
work conducted by the Educational Authorities. That was not exactly what the Authors meant. The Educational Authorities were the executive body with power to move tools, but the work would naturally be grouped and carried out by the trained engineers whom they might have available in their numerous technical schools. Reference was also made by Professor Wells to gauge-making, and the proportion of wasters likely to be obtained at the technical schools. Without going into detail, he would simply say that thousands of gauges had been turned out true to specification, and in one prominent institution the first rejections were not 5 in 100. The rejected gauges had been put right and finally approved, so that the final rejections were not nearly 1 per cent. He was informed that as late as the middle of last summer a very large proportion of gauges was being rejected even from engineering firms.

Communications.

Professor Frederic Bacon wrote that the arrival of this thoughtful and suggestive Paper was most timely, and, taken in conjunction with the discussion it was intended to promote, would doubtless prove most fruitful and far-reaching in its results regarding the immediate and future relationship between technical colleges and the supply of munitions. When peace returned, the vexed question of the proper sphere of the college workshop would have to be looked into again, and from a new and little suspected standpoint, namely, from a point of view in which the War Office would be, or at least ought to be, just as immediately interested as the Board of Education or the Engineering Institution. He hoped that in due course all the engineering colleges of the country would be linked up in a national scheme, which would enable them to train and otherwise provide for a national industrial reserve, ready for immediate and automatic mobilization on the outbreak of another war.

Six months ago, when he had had to choose between undertaking munitions work or the training of munitions workers, he had selected the former, and although it was exceedingly doubtful whether the Authors would have placed his equipment in their "higher category," he had never regretted his decision. Naturally, many technical difficulties had had to be overcome; but these difficulties vanished in comparison with the difficulties which had arisen from local ignorance of the requirements of accurate machining processes, disbelief in scientific methods, and distrust—even amounting to bombastic contempt—for the idea that a teaching institution could possibly handle with success a practical problem beyond the limited range of experience typical of the district. In fact, had it not been for the existence of the National Physical Laboratory to vindicate his claims of accuracy, and another Central Authority ready to receive and act on suitable representations, all his endeavours would have proved unavailing. He was prepared, on the strength of his recent experience, to corroborate and even strengthen the Authors' assertion that many engineering students could very quickly pick up the special grinding and lapping operations necessary in the final stages of gauge-making.

When it was recalled that the chief engineering activities in his present district were in connexion with coal-mining and ship repair, it would be easily understood that trade mechanics possessing "the necessary temperamental faculty of perceiving by touch and gauge very small differences of dimensions" had been simply impossible to secure, and after failing dismally in a few attempts to convert the ordinary "foot-rule man" into the highly specialized tóol or gauge maker, he had ended by relying entirely on a judicious selection of his own students to supplement the efforts of the permanent staff. It was really surprising to find, in this high precision work, how superior intelligence and a little scientific training overpowered years of shop experience of a not quite suitable kind; a middle-aged professional instrument-maker proved a complete failure in working close to absolute dimensions, whereas a scholarship lad who had won his way to college from the smithy and the forge was shaping well on precision work. If required,

(Professor Frederic Bacon.)
this young man, after only two or three weeks at his new job, could knock out a horse-shoe gauge blank on the anvil and then proceed to rough file, harden, grind and finally lap the jaws until the final result was correct to size within one or two ten-thousandths.

At the outset of Section 1 (v) (page 728) the Authors insisted upon the fact that only full-time work was of value. While in entire agreement with their statement of the case, he would like to point out that a short course of voluntary part-time munitions work supplied an excellent means of selecting suitable men for subsequent engagement as full-time workers. Before his senior classes had been entirely suspended, a voluntary part-time scheme had been in operation for a short while. Naturally, nothing of material value had been directly accomplished thereby; but indirectly the scheme had proved a great boon in indicating which were the right students to convert into full-time munitions workers.

An important matter touched on by the Authors was the conditions on which machine-tools, etc., had been lent or exchanged between technical colleges and Munitions Committees, etc. In certain cases machine-tools had been rashly handed over without any very definite stipulation, and it was to be hoped that regulations, or at least guiding principles, would be framed such as would secure fair and uniform treatment all over the country before the final day of settlement arrived.

In regard to the training of munitions workers for the actual machining of shell bodies, it was important to remember that there were other places where such training could be given even better than in the average college workshop and without disturbing the regular shell factories. He referred to repair shops attached to electric power stations, pumping stations, gasworks and the like. Such repair shops were often well equipped with suitably heavy lathes, drilling machines, etc., under the supervision of an engineer of high standing in his profession, and ready manned with a nucleus crew of expert hands thoroughly acquainted with the capabilities of the shop in question. Mr. Arthur Ellis (page 780) had shown him what wonderfully successful results could be achieved in this direction, and had also opened his eyes regarding the immense

possibilities of profitably employing the voluntary part time services of professional, non-technical men when properly organized and directed. He, the present writer, thought the Authors of the Paper had spoken too disparagingly of the work of amateurs. He could think of several—and there must be a considerable number like them—whose skill in fine metal work, such as model making, was of the very highest order, and skill of this kind could be much more readily utilized for munitions work than that of the average non-specialized engineer, say, such an engineer as was suited for taking charge of a small power-plant. There were many long-established engineering works of the rough-and-ready variety which had experienced the utmost difficulty in working up to the requisite accuracy, while small and obscure shops owned and controlled by a man of the right type had attained immediate success in meeting the most stringent requirements.

In conclusion, he would like to acknowledge his debt of gratitude to many members of the Institution, including one of the Authors, for giving him the free run of their works and the benefit of their expert knowledge. Had it not been for their unstinted help and encouragement, it would never have been possible for him to achieve his present measure of success in converting his laboratory repair shop into a shop dealing in considerable volume with munitions work, demanding almost the highest degree of accuracy possible to secure.

Sir Robert Blair (Education Officer, London County Council) wrote that there were many things of importance and interest in the making of munitions which could not at the present time be discussed in public. The Authors, in exercising a natural restraint on themselves, had therefore deprived their Paper of much that would have been very interesting. Further, the Authors had had experience of the manufacture of munitions in certain directions, but not of the training of munitions workers, and on both these heads it might be said that, so far, engineering colleges were yet on probation, though they were gradually asserting their position. The full story could not be told now, and more experience was necessary before any definite conclusions could be generally enunciated.

(Sir Robert Blair.)

The important matter which had been before the Metropolitan Munitions Committee and the London County Council had been the effective utilization of the resources in staff and machinery of the various technical institutions. To effect this, a specialization of functions had been imperative, and the predominant factor in the success of the work, so far as it had gone, had not been so much machinery and equipment as staff. Over 1,800 workers had been enrolled in munitions training classes, and about 1,100 had received certificates for proficiency for their work during a six weeks' course comprising 144 hours' instruction. Persons so trained were now distributed over about 120 different factories, in some of which only a few were employed, but in others as many as 50 and 100. The reports which have been received from individual firms showed, on the whole, that these semi-skilled workers had been found of very great service.

Sir A. Trevor Dawson (Member of Council) wrote, in response to the President, that the Authors, it would seem, generally based their observations on the conditions prevailing in the Metropolis, which, it would be recognized, differed materially from those obtaining in centres where engineering was the dominant or most important industry. From the metropolitan point of view their observations were interesting. The extent and character of the work that a technical college or workshop could do towards augmenting the output of munitions was dependent on the equipment as well as the staff. As this equipment was of a very varied character, necessarily for educational purposes, "repeat" work would be done under conditions not conducive to efficiency either as regards the time taken or the cost. No doubt in the making of gauges and other articles, where great numbers were not required, and where highly skilled and precision work was essential, the instructors, and perhaps advanced students, with their fine appliances, could perform useful service.

The great need for the moment, however, was the maximum output per man per hour, and per machine per hour. Each had to be utilized on the work he or it was best fitted to accomplish, and

had to be operated to the fullest extent possible. It was his experience that, to achieve these ends, munitions work should be done in large factories. The highly skilled men who were now instructors in technical colleges could influence, to a far greater extent, munitions productions in factories where larger bodies of workers were under their control than in colleges now with limited equipment, particularly if they were utilized there for the training of non-skilled workers at particular machines assigned by the foreman to each new-comer. The students could do more work alongside commercial workers than at college; the atmosphere was more encouraging. The lathes could be better disposed if set among their respective classes in factories, and more fully utilized as units of a complete sequence. In colleges the amount of work done would not be commensurate with the extent and value of the supervision given, or the cost involved in the equipment. He (Sir Trevor) suggested this absorption rather than isolated action, the more readily as the Authors stated (page 729) "it is one of the sacrifices demanded by the stringency of the present crisis that at least some of the educational work, and from the conditions that of the higher type, has to be set aside for the present so that the personnel, both students and instructors, as well as the material equipment, may be freed for national service." Where he differed from the Authors was that he thought personnel and equipment should be merged into the great factories making tens of thousands of shells per week, rather than be retained in college workshops producing hundreds.

Again, as to training men and women for factory work, his opinion was that this was much better done in the workshop, and at the very machine whereat the man or woman was ultimately to carry out his or her part in the making of a shell than in the college workshop. College machines, installed for purely instructional purposes, were necessarily so varied that the man or woman trained to work one or more of them might ultimately be called upon to operate a different one in the factory. Furthermore, the example of the expert alongside, and the obvious stimulus of the wage earned by others in a factory, increased the eagerness of the learner

(Sir A. Trevor Dawson.)
to become expert. But, as he had already said, the college instructors, and perhaps also the advanced pupils, would be most serviceable in training the unskilled workers in the shops—a work for which their qualifications rendered them specially suitable.

Mr. Arthur Ellis wrote that he considered the Paper was one of a most interesting character, and he could speak from experience in this respect in consequence of having had such valuable assistance from the local University College, and in particular the head of the engineering department, who had for some time past taken a keen interest in the manufacture of gauges necessary for shell-making by utilizing their equipment, aided by his permanent staff and a number of trained students. Had it not been for these gauges, the work of shell-making which was being carried on at the writer's works would not have reached the present advanced stage of development.

The members might be interested to have a few details relating to the work of shell-making that had been undertaken in the little workshop attached to the Power Station. Some time ago the writer and a number of personal friends, comprising professional gentlemen, volunteered their services during the week-ends, free of cost, in any factory within 100 miles of the city, to assist in the manufacture of munitions, and to relieve the regular workers during the week-ends. Whilst this offer brought forth an expression of appreciation, it was not taken advantage of. Subsequently the writer made a proposal to the local Munitions Committee, to assist them to some extent by manufacturing shells in his own workshops, and so help forward the output in the particular district. This offer was accepted and much appreciated, and was working remarkably well, but the writer felt it was due to the professional gentlemen who had given, and were still giving, so many hours of their spare time, that such services as those rendered by them should receive the recognition that was due to them.

Shell-making was only carried on during the spare hours and week-ends, as during the ordinary hours of the day, namely, from 6 a.m. to 5 p.m., and until 1 p.m. on Saturdays, the usual work

connected with the operation of the Power Station had to be carried on, and in consequence of which the machine-tools were fully occupied; but upon completion of the day's work, and after a short interval to clean the tools, etc., shell-making started, the volunteers commencing duty at 6 p.m., working in two shifts of six hours each until six the following morning, throughout the week, with three shifts on the Saturdays and Sundays, so keeping the machine-tools occupied during the whole of the spare hours of the week. The volunteers were drawn from professional gentlemen, none of whom had previously had any mechanical training, and comprised solicitors, architects, accountants, shipowners, coalowners, etc. The experience that the writer had so far obtained had convinced him that the unskilled individual was more useful and more accurate in shell-making than the skilled operator usually found in workshops, except in those shops where very special work was carried on; and even in those cases, with modern automatic machines, and particularly so, the individual who worked during his spare hours (for the love of it only) realized the important character of the work upon which he was engaged, the importance of avoiding mistakes, and he always had present in his mind the fact that in some instances he was working to a thousandth part of an inch, or less, with the result that he exercised extreme care, in addition to which such people were able to appreciate the importance of this fine work.

It naturally took some little time to train the volunteers, but it was remarkable the speed with which they seemed to grasp the handling of the tools, etc., and to-day they had seventeen different shifts working throughout the week. He thought that there was not an individual on any shift who was not able to go straight to his machine and carry on his work in a satisfactory manner under the supervision that was provided from members of the writer's staff, who were likewise keenly interested in the work, and devoting a great deal of very valuable time to the same. The number of tools available was of course limited, but they were hoping to receive other necessary additional tools, which would enable the existing output to be doubled or even trebled. The

(Mr. Arthur Ellis.)
regularity with which the volunteers turned up for their work was remarkable, and not one of the machines was idle for a single hour. Each volunteer worked two duties per week, of six hours each. He gave his time absolutely gratuitously, whilst the writer's department furnished the use of its machines, tools, equipment, light, heating, and everything else free of cost, the only cost borne by the local Munitions Committee being that of the steel bars. The work was carried on in a regular manner; each volunteer had a time sheet, upon which he booked up the output during any one duty. The time sheets were signed by the volunteer who was looked upon as the leading man in charge of the turn, under, of course, the supervisors, who were provided from the writer's assistants; and a careful record was made, not only of the number of hours worked by each volunteer, but of the actual work that he had performed. This was done for the purpose of supplying to each of these gentlemen at the end of the War a complete return of his contribution—in time and output—towards the manufacture of munitions.

Mr. Thomas T. Heaton wrote that he understood the Authors recommended the employment of the staffs of the Technical Colleges for the training of persons who might proceed therefrom into factories engaged in munitions work. The persons whom it was proposed to train were those with no knowledge of the kind necessary, seeing that trained or semi-trained people were not available.

The discussion dealt with the method of the training in question; some speakers approved of a sort of general training and others thought differently. Having had to deal with this kind of thing in the organization of the works where he was engaged, he (Mr. Heaton) thought that his own experience might perhaps be useful to other members. He was under the impression that the work under discussion was "repetition work"—that is to say, work consisting of large numbers of similar articles. This was the only kind of work to which rapid training could apply, as adequate general training took too long under existing circumstances. He had dealt with this kind of work by employing persons without any

previous experience at all connected with the work to be done, and therefore with no preconceived ideas. Each person was set to one class of work only and kept at it, with one end in view, namely, to do his one job over and over again and produce an accurate result. This ensured the proper beginning of the next operation in the sequence and the starting of the next man's job on an economic basis. With proper instruction and supervision, he had found this plan to work admirably.

It would follow that if a college were to undertake the training of persons as suggested, the principle adopted should, in the writer's opinion, be to specialize in the operation the said person respectively would be required to perform. The advantages of this system were obvious, as all sorts of persons could be made into skilled workers, each in his or her own sphere. To make the system practicable, agreement was necessary between works managers in need of men and the college staffs, so that the need might be first specified and then supplied. The colleges would need the apparatus for training.

He could not understand why the fact of women having proved such good munitions workers should cause wonder. If the work were not too heavy, women were quite as capable as men and often much more so than the hybrid workman of to-day, whose mind was often divided between football and his rights, but never occupied itself with his duties.

Professor H. H. Jeffcott wrote that for some time past they had been working day and night at his College on the manufacture of fuze parts and they were making arrangements for considerable developments. In the first place, capstans and special chucks were made for several ordinary lathes, thus converting them into semi-automatics. They had also made practically all their jigs and tools: taps, dies, hobs, cutters, box tools and form tools of many kinds. In addition to the manufacture of munitions, they were also engaged in the training of munitions workers.

Engineer Rear-Admiral Edwin Little wrote that inspection, on behalf of the Ministry of Munitions, of the work in progress in

(Eng. Rear-Admiral E. Little.)
engineering workshops of the Technical Institutions, which were co-ordinated under the London County Council, had formed, till quite recently, a part of the service he had been endeavouring to contribute to the National cause. The special acquaintance with the work of these institutions thus afforded him might warrant a few observations, if only by way of testimony to the excellent results obtained.

The workshops were mostly small and the plants of machine-tools were arranged rather for instruction than for output or reproduction. The tools were mostly light machines and served to illustrate the principal operations involved in ordinary manufacture. In very few cases were there any automatic or semi-automatic tools available. Except at the Imperial College, none of the shops could be regarded as adequately equipped even for good technical instruction in modern workshop practice. Generally speaking, the machines suffered from the repeated first attempts by the beginners during successive courses of instruction, and, without considerable refitting, could not be relied upon for any really accurate work. The instructional staffs included several highly skilled men of the type usually selected to be employed as tool-setters, first-class gauge and jig makers, charge men, and shop foremen or managers in large and important works. The principals of the institutions were actuated, as would be expected, by a high standard of technical achievement, and a well-trained conception of the underlying principles and methods by which alone close accuracy of form and dimensions could be realized in practice. With a very uncertain and doubtful supply of labour, and notwithstanding inadequate appliances, the resourcefulness and good organization in the division of the work, and in adapting the appliances available, they have accomplished much really good work, and have maintained the standard of accuracy and the fine limits mentioned in the Paper. The gauges made included ring, plug, and screw gauges, some position gauges of a difficult and intricate kind, and a large number of plate gauges needed for the examination of fuzes and shells. The ten or eleven institutions employed have produced over 4,000 of such gauges, which have been subjected to very

unsparing and rigid examination by the National Physical Laboratory.

Side by side with this work, the usual engineering courses of instruction have had to be maintained. In one institution the writer was desirous of discussing the design of a special jig for simplifying the manufacture of an intricate fuze, and found the designer fully occupied in lecturing at a blackboard to a class of students in applied mechanics involving a long calculation. In some of the shops, in order to keep the younger students occupied, it has been found necessary to take sub-contracts for details of gun mountings, transport lorries, air-craft parts, and other details of a simple kind, and this interchangeable work has been very successfully organized and carried out.

It was in the training of partly skilled workers that the institutions have done most excellent service. Having taken in past years a considerable part in the workshop-training of partly skilled mechanical ratings in the Navy, he (Admiral Little) was well able to appreciate the really amazing results achieved by a most cleverly graduated step-by-step course of some six weeks' duration at one of the colleges, and he was glad to have an opportunity of congratulating the London County Council upon possessing such able and discerning instructors upon their staffs. To the large amount of technical training for war work, other than for engineering, done by the institutions, it was not necessary here to refer. About 1,500 willing munitions workers have passed through three of the institutions, and nearly 1,200 have been granted certificates of usefulness. About 80 per cent. of these were, he understood, actually employed in munitions works, not as fully-trained mechanics, but with clear notions of accurate measurement, a workshop sense of touch—a sufficient knowledge of tools and material to be safely and satisfactorily employed, after a few days' practice, upon some one or more of the operations involved in shell manufacture.

However, he did not consider this was a function that, after the war ended, these institutions should be again engaged upon. He hoped such hastily-devised means of production might never again be relied upon, should the Country be again engaged in so stupendous

a struggle. The need of preparation and timely organization of all the engineering trades for national defence would surely have been too deeply impressed upon them, nor did it appear desirable that these small workshops should be equipped for manufacture or production, and that much more valuable service could be given by the very fine staff of practical and highly intelligent instructors, by taking part in the management and direction of national workshops fully equipped with up-to-date tools, and where the output of components was counted in several thousands rather than a few hundred per week.

Mr. David A. Sheret wrote that, in his opinion, to fulfil the object of their purposes colleges should be educational, and not in the rearguard to the extent of sixteen months. Had technical colleges proved their capacity, no one would deny that prominent engineering firms would have appreciated their work in practical training, but this had not been so, and one must appreciate the management's decision in this matter when they said that the advantages of such training were negligible. To suggest that they could train men to be gauge-makers to any degree of exactness, when engineering firms with large numbers of employees found the class fitted for such work extremely scarce, failed to meet with the commercial engineers' approval; and that if they sought to have efficient teachers in this line it would deplete important works of the best men, due to the general terms given when public moneys were to be used.

Centralization, to be worthy of recognition, would only be useful in such an abnormal condition as the present, and would entail expenditure out of proportion to the benefits resulting therefrom. To establish costing arrangements, etc., was too Arcadian to be practical, and would also prove financially wasteful. It would be more effective if the colleges carried out more laboratory investigation work, for instance, on crude-oil internal-combustion engines. Mechanics could produce such machines economically and commercially, allowing that they had the necessary plant. To train an engineer, he should not learn to use automatic machinery; in fact, a hand-lathe would be preferable to a capstan—there he was required to use his head equally with his hands.

No one would be foolish enough to suggest that munitions were being produced economically at present; the costs went up by leaps and bounds, and it would be well if the Government looked to the stock of munitions in times of peace rather than rushed to projects which the highest and best authorities feared for an instant to deal with. When controllers of shipping, finance, and coal production were first installed, and only when the common voice of those who knew prevailed, did the engineer find his services sought.

Professor W. H. Watkinson wrote that the object of this Paper was, in the main, admirable, and it would have been much more useful if it had been written and discussed six months ago. Rapidity of output of munitions of war and of all things necessary for their production was, at the present time, of the most vital importance. The maximum rate of progress could not be attained if machine-tools were not employed continuously day and night. Another condition for maximum rate of production was that the machine-tools and men should be concentrated in factories of considerable size, as, otherwise, too much time was expended in distributing the raw material, in inspecting and testing the products, and in collecting the finished products. These conditions could not, in general, be attained in a school or college workshop, and he thought that the Ministry of Munitions ought, without delay, to take over and concentrate in factories, all suitable machine-tools and all skilled men, whether teachers or students. Even in the manufacture of gauges there was great dissipation of energy when these were manufactured either in college workshops or in small private factories. The best results would be attained if all the gauges required in the country were manufactured in two or three factories at the most.

In June of this year it was decided that the best way in which the machine-tools in the University with which the writer was connected could be utilized was in the manufacture of shells in a local factory, and the tools were immediately lent for this purpose. Shortly afterwards they were asked to undertake the manufacture of gauges, also to start classes in the elements of turning for persons

(Professor W. H. Watkinson.)

desirous of working in shell, fuze, and other munitions factories. To enable them to do both of these things, they appealed to amateurs and others for the loan of lathes, and they soon succeeded in obtaining a sufficient number of machine-tools quite suitable for the above purposes, although they were not sufficiently powerful for use in a shell factory. They were also fortunate in being able to enlist the services of a considerable number of skilled men, including about a dozen instructors from manual training schools in the city. Nearly every one on the writer's staff, and many of the above men, sacrificed their summer holidays, and during the long vacation they succeeded in constructing over 1,500 gauges for shells and in giving instruction in lathe work to nearly three hundred men and women. These were absorbed into munitions factories as rapidly as they were trained. A considerable number had, of course, to be rejected during their training owing to their lack of adaptability.

The Authors, in replying to the written Communications and in further reply to the Discussion, would deal as far as possible seriatim with some of the more salient points raised, realizing that space would not allow them to refer in detail to all the valuable suggestions and criticisms advanced by speakers and correspondents.

Mr. Armstrong's samples of work, executed in the factory with very little training by previously unskilled workmen and lads, were good examples of what could be accomplished by intensive training on single operations with or without the aid of jigs, and his suggestion that it was less necessary for the technical institutions to lay themselves out for such training was aptly enforced by the statement that "about 100 workers had been trained in the L.C.C. schools, but unfortunately they had to be specially trained for the modern machines."

In this connexion Mr. Wigglesworth's remarks on page 766 were valuable as coming from one who had had good opportunities of collecting expert opinion of the value of the workers produced by courses of so-called general training, and who also had a good

knowledge of the "purposes of the Ministry of Munitions in issuing the circular which was referred to in the Paper." As Dr. Garnett remarked, the "business now must be production and not education."

With reference to the same point, Sir Trevor Dawson in his written communication (page 779) stated that the training of munitions workers "was much better done in the workshop, and at the very machine whereat the man or woman was ultimately to carry out his or her part," and Mr. T. Heaton emphasized the point (page 783) that each person should be "set to one class of work only and kept at it, with one end in view," namely, to specialize in one operation.

These and the other statements made showed, and the Authors concurred, that training to be of immediate value in the munitions factory should be confined to the single operation on the type of work and tool upon which the worker would be employed. It might also be stated, and with a good deal of truth, that for this purpose general instruction courses at technical colleges had another value. They enabled the authorities to select workers likely to be useful as munitions workers in the factories; but in this respect there was a danger that the cost of general instruction courses which were being given to would-be workers would throw a very severe charge on the already heavy cost of munitions. When it was kept in view that a schoolboy fresh from school, or any intelligent person, could be placed directly in a munitions factory, and could acquire in a few hours the necessary ability to carry out a simple operation controlled by jig work or through the mechanism of a capstan lathe, it would be realized that a good deal of waste in material, skilled staff, tool facilities, etc., was involved in carrying out elaborate and graduated courses of instruction which could not possibly be utilized, and which could not possibly give to the worker the degree of accuracy required in the processes dealt with.

The remarks of Mr. H. G. Taylor (page 762) had been so completely answered by the speakers whose comments have been alluded to above, that the Authors felt it was not incumbent upon

(The Authors.)
them to analyse his contribution further, and they were therefore content to place on record a general dissent from most of his arguments and conclusions, and their disapproval of his course for training munitions workers.

With reference to Dr. Garnett's remarks (page 757) on the workman of the future, the Authors agreed that although the tendency was distinctly towards specialization, there would in ordinary times always be room for the type of worker trained concurrently in non-specialized works and works not capable of being specialized, and their observations on page 741 should be noted in this connexion.

The Authors were entirely in agreement with Dr. Garnett in his views (page 757) as to the desirability of installing modern capstan lathes in first-class college workshops, and while they thought it could be shown that there was a proper place in the college workshop for some of the highest specialized tools, yet they further agreed that the older tools and workshop methods should receive a first and very prominent place. In this connexion it might be remarked that the question of the relation of college workshop equipment and training to certain aspects of the training of mechanical engineers had not yet been properly understood by the Education Authorities or even by many engineering teachers.

Dr. Garnett's recommendation on the hardening of gauges (page 761) was a practical one which would have saved much trouble and much material had it been adopted, and the Authors had found the notes which he sent to them in the early days of munitions manufacture to be of practical value.

Dr. Garnett's statement, that in the majority of cases roughing-out operations took far less time than the finishing, needed a little qualification, for the relative time taken depended upon the nature of the work to be done. For example, in gauge work the grinding-out operations on a universal machine could often be done very much more quickly than the roughing out of the gauges preparatory to grinding; but as stated by Dr. Garnett, the ordinary engineering schools could boast of a dozen tools suitable for roughing as against one for the more accurate work, and it was in this respect that the

roughed-out gauges accumulated more rapidly than finished ones. The remedy in such cases was to secure a higher proportion of work which could be finished by the ordinary machine operations, including work which could be carried out on capstan lathes or repetition machines, so as to keep the less-skilled workers fully employed whilst the relatively few highly-skilled men were finishing the gauges.

Professor Wells's remarks (page 768) expressed a caution of which very careful note should be made. Education Authorities undertaking the manufacture of munitions should throw the whole responsibility and direction on their skilled engineering staff, as unless this were done serious mistakes would be made, and the cost of the munitions work would be altogether out of proportion to the value of the work done.

Dealing next with the written Communications, the Authors were in agreement with Professor Bacon's statement, but they regarded the matter from another point of view than the one he mentioned (page 774), that "when peace returned the vexed question of the proper sphere of the college workshop would have to be looked into again." They desired to add that the old ideas which had hitherto largely prevailed as to the proper function of the college workshop could no longer suffice. The Authors were in agreement with those ideas so far as they went, but they did not go far enough, and excluded special considerations of vital importance in connexion with mechanical engineering. The Authors were interested to learn that Professor Bacon had achieved so much in the face of considerable difficulties and prejudices.

The few statistics given by Sir Robert Blair (page 778) and Admiral Little (page 785), as well as those given by Dr. Garnett, on the training of munitions workers by the London County Council, were interesting. The Authors stated on page 720 that "on the outbreak of war it was inevitable that the work of the technical colleges in relation to it should be put on its trial," and they noted that Sir Robert Blair was in agreement with them when he stated in relation to manufacture and the training of munitions workers "that, so far, engineering colleges were yet

(The Authors.)
on probation, though they were gradually asserting their position."

Sir Robert Blair also stated that the Authors "had had experience of the manufacture of munitions in certain directions but not of the training of munitions workers." The Authors regretted that, for military reasons, it was impossible to give details of manufacturing work or other expert work done by them or carried out under their direction. Had they been able to do so, much support would have been given to certain statements made by them in the Paper. The last part of Sir Robert Blair's statement, that the Authors had had no experience in the training of munitions workers, was incorrect, as was shown in many parts of the Paper, and also inasmuch as workers had been trained by them in the direct manufacture of munitions. The Authors were of opinion that short graduated instruction courses were not the kind of work which would be of value in the munitions factories, and their views on this point had received ample confirmation by the various speakers and correspondents.

The Authors were pleased to note that Sir A. Trevor Dawson was in agreement with them when he stated that, "in the making of gauges and other articles where great numbers were not required," instructors and students could perform useful service. It was just in this respect that the best of the college workshops were doing such good work, and the Authors strongly held the opinion that work more effective and more valuable to the country could be done in such college workshops by keeping their plant, staff, and students together as a manufacturing concern than by distributing the personnel and equipment amongst a number of factories. These remarks applied, however, only to a few of the college workshops, as mentioned in the Paper. On page 723 the Authors, as an example of what might be done by the Education Authorities in a large area, said "it would be quite possible to obtain an output of 200 to 600 shell-bodies per week." Sir A. Trevor Dawson (page 779) stated his opinion that "he thought personnel and equipment should be merged into the great factories making tens of thousands of shells per week, rather than be retained in college workshops

producing hundreds." To this the Authors replied that it was not quite fair to compare the output of a single unit with that of a number of factories taken together. Moreover, many munitions firms making shell-bodies did not exceed the small output stated. Since, however, the above was written they were of opinion that still more suitable manufacturing work, as outlined in the Paper could be undertaken by the college workshops.

Mr. Arthur Ellis's contribution was of much interest as showing what could be done under difficult conditions, but under expert direction, by professional men without previous training, working from purely patriotic motives. Mr. Ellis's system, whereby each worker would have supplied to him at the end of the war a statement of the value of "his contribution—in time and output—towards the manufacture of munitions," was a stimulating one, and was perhaps about the only suitable return which could be made to these men working with such high motives.

The communication of Engineer Rear-Admiral Little bore testimony to the valuable work which the college workshops had done and to his appreciation of that work. The Authors were not fully in agreement with the Admiral's statement (page 784) that "Except at the Imperial College, none of the shops could be regarded as adequately equipped even for good technical instruction in modern workshop practice." They agreed that, without a single exception, the equipment was in certain directions inadequate, but they could prove from actual results that in these workshops good technical instruction could be and had been given in modern workshop practice, and that, moreover, certain intensive training over short periods of time, given to apprentices, learners, improvers, and to engineering students generally, was far wider and even more thorough than could be obtained in anything like the same time spent in the works of most engineering firms.

The Authors agreed with the opinion of Mr. D. A. Sheret (page 786) that "colleges should be educational," as he was evidently referring to college work under ordinary peace conditions. They could not, however, accept, as he implied, that the colleges were "in the rearguard to the extent of sixteen months." They did not

(The Authors.)
know of any prominent college to which this could apply. Nor did the Authors agree with the unqualified and sweeping statement made by him that in any large or preponderating number of cases the management of prominent engineering firms had arrived at the decision that the advantages of college workshop training were negligible, nor with the further remark "that to suggest that they could train men to be gauge-makers to any degree of exactness . . . . failed to meet with the commercial engineers' approval." The facts given in the Paper, the Discussion and the written Communications showed these statements to be fallacious. It might further be pointed out that the manufacture of some 5,000 gauges by the London college workshops, setting free something like sixty commercial engineering factories for the manufacture of the munitions for which these gauges were required, must and did meet with the manufacturers' approval at the present time of national crisis. The college workshops had been successful in gauge work where many commercial engineering firms had failed. The best colleges did not, as implied by Mr. D. A. Sheret, seek to obtain efficient teachers in gauge-making from important works; they already had teachers possessing these and other qualifications on their permanent teaching staff, and these men, who were capable teachers in other directions, were now working as gauge-makers and also giving instruction to less-skilled men and boys in the college shops.

Mr. D. A. Sheret stated that "to establish costing arrangements, etc., was too Arcadian to be practical and would prove financially wasteful." He would be interested to learn that "Arcadia" had been realized, and that not only was the scheme outlined by the Authors in use in at least one institution, but that all colleges had some system of arriving at the cost of the work done. Mr. Sheret referred to laboratory investigations, and here the Authors were in full sympathy with his remarks. That more investigation in the laboratories was not done was due to the neglect of successive Governments, and, it must be added, of Education Authorities, in not appreciating the importance of scientific research and scientific technological training, and providing the necessary funds to be administered under real expert advice.

Professor W. H. Watkinson's remark, that the Paper "would have been much more useful if it had been written and discussed six months ago," overlooked the fact that, at the period referred to, the experience and facts utilized in the Paper had not accumulated. At that time much which has now been ascertained would have been matter of conjecture only. Professor Watkinson's own experience appeared to have been unfortunate and due to a lack of prevision at about the period named as to what would be required in the immediate future, and the Authors sympathized with him in the difficulties subsequently encountered in consequence, and congratulated him on the methods adopted to meet these difficulties. His staff, of course, was not the only one which sacrificed its summer holidays to the pressing necessities of national service.

In consequence of certain criticisms which had reached them, the Authors thought it necessary to guard against a misunderstanding which had arisen, as to their views of the relationship of the college workshop to a properly co-ordinated course of study in Engineering. The Paper was on "Engineering Colleges and the War," and in it they had therefore dealt primarily with the college workshops in relation to the War—an emergency relationship which had never previously occurred in the history of any country, and which, it was to be hoped, might never occur again. To avoid any such misunderstanding, they stated here that it was not the proper function of any engineering college to attempt to teach a trade or to attempt to give what might be called full instruction in modern workshop practice to students attending full-time engineering day courses. The college workshop in relation to day students had different functions altogether, and played a smaller though important part in connexion with their general educational work.

For evening students, however, the case was quite different, and much had been done in giving sound workshop instruction to men desiring to supplement a narrow, inefficient, and specialized practical training so as to make them better workmen. There were other important functions of the technical college workshop for both day and evening students, which could not be dealt with here without a digression quite outside the limits of the Paper.

(The Authors.)

In conclusion, the Authors desired to express their cordial thanks to the speakers and writers who had stated their opinions and given the results of much practical experience in dealing with workmen of different types in relation to the manufacture of munitions, either in commercial works or in the college workshops, and also of the value of the work done by the Engineering Colleges in relation to the War. The Paper, discussion, and correspondence, would undoubtedly be of much value to Government Departments and to the Education Authorities in helping towards the end that all had in view. The Authors ventured to hope, therefore, that their main object in writing the Paper had to some extent been attained.

MEMOIRS.

Edward Backland Stuckey Aston was born in London on 20th July 1868. He was educated at Christ's Hospital, and in 1886 became apprenticed to Mr. E. Hayes, Stony Stratford. Three years later he went to Messrs. J. Penn and Sons, Greenwich, with whom he remained until 1891, when he was engaged as erecting engineer by Messrs. Willans and Robinson. He left this firm in 1893 and went for a few months to Mr. A. G. Mumford, Colchester, as draughtsman. In 1894 he received an appointment in the locomotive department of the Midland Railway at Derby, but left in 1896 to take charge of Government workshops and marine plant in Lagos, West Africa. His health failing, Mr. Aston returned to England in 1898, and, after taking charge of cement kilns for the firm of Messrs. Francis and Co., Rochester, for some six months, was engaged as engineering expert by Messrs. John Batt and Co., Ltd., London. He left in 1904 to go to Messrs. Cammell Laird and Co., as one of their London representatives, and in 1909 started business on his own account as engineering merchant and contractor. His death took place in London on 30th October 1915, at the age of forty-seven. He was elected an Associate Member of this Institution in 1901.

William Bardill was born at Ironville, Derbyshire, on 24th January 1860. He was educated at various schools in Sheffield and at Nottingham University from 1890 to 1893, where he gained a County Council Scholarship. He served an apprenticeship of three years, 1874 to 1877, at Butterley Ironworks, and a further apprenticeship of four years, to 1881, as an improver at Turner's Rolling Stock Works, Langley Mill, Notts. He stayed with the latter firm until 1900, occupying posts which varied from leading iron turner to manager, in 1896. From 1900 to 1904 he was manager to Messrs. Heenan and Froude, Ltd., and from 1904 to 1910 manager

to The Wantage Engineering Co. He finally settled in Nottingham as a consulting engineer. Mr. Bardill had great experience in mining and railway machinery. He wrote several Papers on Gas and Oil Engines, the Engineering of Collieries, the Commercial Management of Engineering Works, etc. His death took place at West Bridgford, Nottingham, on 13th September 1915, in his fifty-sixth year. He was elected a Member of this Institution in 1910. He was also a Member of several Mining Institutions and Societies.

John Barr was born at Kilmarnock on 1st April 1855. Entering the office of Messrs. Glenfield and Kennedy, Kilmarnock, as a youth, he rose to be secretary of the company, and latterly filled the position of managing director. His mind had a distinct bent towards mechanical engineering, and, although he did not undergo a practical training, he spent a considerable part of his time about the works, gathering much knowledge of engineering generally. He saw the development of the Glenfield Works from a comparatively small undertaking to one of the most important engineering concerns in the country. Mr. Barr travelled extensively in the interests of the company, having visited the United States and Canada, South America, South Africa, Australia, and New Zealand, and much of its success was due to his energy and enterprise. In 1905 he contributed a Paper to this Institution on "Waterworks Pumping Engines in the United States and Canada." He had been in poor health for several months, and had sustained a severe blow by the death of his eldest son, Mr. James Barr, who, with his wife, was lost in the sinking of the "Lusitania" by a German submarine. His death took place at his residence in Kilmarnock on 12th August 1915, at the age of sixty. He was elected an Associate of this Institution in 1889; he was also a Member of the Institution of Engineers and Shipbuilders in Scotland.

George William Blackburn was born at Seacroft, Leeds, on 2nd October 1859. He received his technical education at the Leeds Mechanics' Institute, and in 1874 started on a four-year term

of apprenticeship with Messrs. Kitson and Co., Ltd., Airedale Foundry, Leeds. He remained with this company as draughtsman until 1884, when he went to Messrs. Thomas Green and Son, Ltd., Leeds, as draughtsman, and designed their compound atmospheric condensing tramway engine. In 1887 he became assistant manager of the firm, in 1892 manager, and managing director in 1900. This position he was holding at the time of his death, which took place suddenly in his office on 10th November 1915, at the age of fifty-six. He was elected a Member of this Institution in 1891.

Edwin Charles Carnt was born on 24th May 1858. His early career began in the Royal Navy; he entered Portsmouth Dockyard as an engineer student in 1873, passed through the Royal Naval College, Greenwich, in 1879, and commenced his services as assistant engineer the following year. He saw active service almost at once, being present at the bombardment of Alexandria, on board H.M.S. "Alexandra," and earning distinction for bravery and readiness of resource in the subsequent landing; for this he received the Khedive's medal and star. After passing some years afloat in various ships, he acted as assistant engineer during the construction of the three vessels of the "Leander" class at Napier's, afterwards being appointed senior engineer to the "Leander"; he remained on board this vessel for some years on the China Station. His energy and organizing abilities marked him out for a superior position, and he was appointed in 1889 overseer at the Naval Construction and Armament Works, Barrow-in-Furness, which position he held until 1892, when he became assistant to the Chief Engineer at Portsmouth Dockyard; there he took charge of the drawing office, and was intimately connected with the design and manufacture of machinery for the ships of the Royal Navy building at that period. Four years later he was promoted to be engineering assistant to the Director of Dockyards at the Admiralty, with seniority of a staff engineer. About this time the works of Mr. John Samuel White at Cowes were entering the period when the rapid development of the size and power of torpedo boats necessitated some change in their manufacturing system. Mr. White had till then relied on

outside firms for the construction of the propelling machinery of the hulls which he was building at East Cowes. He had already foreseen the increasing importance of torpedo craft, and of the larger type of ship—the torpedo-boat destroyer, which was destined to replace them. Mr. Carnt was thereupon invited to join the firm in 1898 as manager of the engineering works. Here his organizing powers were given full scope, and the works were developed with astonishing rapidity and success. From manager of the engineering department he became sole managing director of the firm, Mr. White having retired from active participation some years before his death. Destroyers of the largest type, power, and speed have been built and engined by the firm during the last few years, and the highest standard of workmanship was attained. He also developed the manufacture of Diesel engines of the two-stroke cycle type, and other internal-combustion engines for smaller powers, the construction of which became a speciality of the firm. The building of sea-planes was also commenced, and under his supervision a large new factory for this class of work was erected at West Cowes, many successful machines being constructed. His death took place at East Cowes, Isle of Wight, on 5th August 1915, at the age of fifty-seven. He was elected a Member of this Institution in 1899. He was also a Member of the Institution of Civil Engineers and a Member of Council of the Institution of Naval Architects.

Captain William Casson was born at Portmadoc on 18th August 1873. He was educated at the Grammar School, Ruthin, North Wales, and at the City and Guilds Central Technical College, where he obtained the Diploma of Associate of the City and Guilds Institute. From 1893 to 1895 he was with the Electrical Installation Co., Ltd., after which he was for four years at the Elswick Works of Messrs. Sir W. G. Armstrong, Whitworth and Co., Ltd. In 1899 he became engaged, together with Mr. H. F. Parshall, on designing, erecting, and testing. He was chiefly concerned with the work of planning and building the London United Tramways and the electrification of the District and

Metropolitan Railways. He joined the staff of the Central London Railway as chief assistant to Mr. Grove in 1907, and remained as chief assistant to Mr. Agnew after the amalgamation of the Central London with the Metropolitan Railway.

Captain Casson was an enthusiastic member of various Volunteer Regiments for twenty-five years. He attained his rank in 1903 in the 7th Battalion, the London Regiment, and at the outbreak of war undertook Imperial Service obligations. On 25th September 1915 he was commanded to lead the British attack at Loos on the extreme right flank, and to seize and hold a dangerous but highly important position. This he accomplished with a skill and courage that was the admiration of all who witnessed it, but he was instantaneously killed by a sniper as he stood on the parapet of the trench rallying his men. He was elected an Associate Member of this Institution in 1904, and was transferred to full Membership in 1912.

Edward Vinicombe Davy, one of the Penzance family to which Sir Humphry Davy belonged, was born in London on 11th December 1883, and was educated at Seaford College, Sussex. In 1901, at the age of seventeen, he began an apprenticeship with Messrs. Glenfield and Kennedy, Ltd., of Kilmarnock, and on its completion in 1904 he studied for two years at the City and Guilds Technical College, Finsbury, where he obtained the Mechanical Engineering Diploma. He then became assistant to Professor Coker at the Finsbury College for one year, and was next engaged on survey and general civil engineering work in the office of Mr. H. H. Hellins, M.Inst.C.E., of Exeter. In August 1908 he went to South America as outside assistant to the divisional water engineer on the Cuyo Division of the Buenos Aires Pacific Railway. For some time he was in charge of the water service installation for Puente del Inca Station on the Argentine-Transandine Railway, but owing to the high altitude (about 8,900 feet above sea level) he suffered considerably from mountain sickness, and was transferred to a lower section. He was appointed chief draughtsman with the survey party on the Rivadavia Branch of the Buenos Aires Pacific Railway, near

Mendoza, and remained there until the construction of the line was finished. Early in 1910 he was appointed assistant to the survey engineer in the San Juan Province, where several branch lines were in project. He remained in San Juan till construction work was started, and subsequently, as assistant to the constructing engineer, was in charge of all outside work on the Marquesado Branch, Santa Lucia Circuit, and the Caucete-Albardon Branch, all in the Province of San Juan. These lines are in the irrigated zone of the Cuyo Division, involving numerous culverts and bridges. At the time of his death, which occurred suddenly at Panqueua, near Mendoza, on 30th June 1915, in his thirty-second year, he was in charge of the remeasurement of the line. He was elected a Graduate of this Institution in 1907, and an Associate Member in 1912.

Hugh Shaw Dunn was born at Riccarton, Ayrshire, on 21st January 1842. He served an apprenticeship at the Townholm Engine Works, Kilmarnock, from 1857 to 1862, when he joined the firm of Messrs. A. and I. Inglis, Glasgow. In 1864 he was for a few months with Messrs. Denny, of Dumbarton, after which he went to Messrs. A. Barclay and Sons, Kilmarnock, with whom he remained until 1866. In that year he was appointed engineer and general manager of the Caprington Collieries, Kilmarnock, which position he held until 1912, when he retired. His death took place at Kilmarnock on 2nd September 1915, in his seventy-fourth year. In 1903 he wrote an Appendix to a Paper read before this Institution on the Newcomen Engine, with reference to a similar engine at the Caprington Collieries. He was elected a Member of this Institution in 1890.

Robert Hammond was born at Waltham Cross, Herts, on 19th January 1850, and was educated at the Nunhead Grammar School. In the "Seventies" he became interested in the importation of iron ore into Middlesbrough. It was in connexion with this undertaking as well as his engineering business in London that in 1878, he took up electricity with a view to applying it to

the development of his schemes. He was the first to advocate electric lighting in this country—he even claimed that his house at Highgate was the first in Europe to be lighted entirely by incandescent electric lamps. Becoming the first *concessionnaire* of the Brush Electric Light Corporation, Ltd., he was highly instrumental in ensuring the success of the Brush arc machine in this country. In connexion with the invention of the Swan incandescent lamp, he devoted his attention to centralizing power, and to distributing current by high tension. He laid down the first plants of this kind in this country, namely, at Brighton, Eastbourne, and Hastings. In 1883, and again in 1888, he went to the United States, where he visited the leading electric light stations. With the view to studying the progress made in electric traction, he, later, paid two more visits to the United States, in 1901 and 1903. Mr. Hammond put down the supply works of numerous towns in this country and abroad, among which may be mentioned Ayr, Blackpool, Burton-on-Trent, Canterbury, Coventry, Dublin, Gloucester, Hackney (London), Hornsey (London), Leeds, Madrid, Malaga, Mansfield, Middlesbrough, Newport (Mon.), Pembroke, Rathmines, St. Helens, Wakefield, and West Brompton (London). In connexion with these undertakings he acted mostly as consulting engineer, though he was contractor for one or two of the earlier ones. He also carried out various extensions of municipal works.

In conjunction with many of the above schemes, Mr. Hammond supervised the installation of refuse destructors, the largest of which, in the Rhondda district, has but recently been completed. In the matter of electric tramways, he was associated with the development of a number of places such as Middlesbrough, Exeter, Rhondda, Bloemfontein, etc., and acted in 1910 as arbitrator between the Paisley Tramways Co. and the Paisley Corporation, and also in 1911 between the Gravesend Corporation and the tramway company of that town, in regard to the price to be paid for electrical energy for traction purposes.

As an expert witness Mr. Hammond's services were in frequent request at Parliamentary Committees. He also acted for the London

County Council in connexion with its Bulk Supply Bills, in 1906 and 1907. In the latter year he prepared a scheme, together with Mr. H. F. Parshall, for the supply of electricity in bulk to Greater London. A Bill was introduced to this effect in Parliament in 1908, but after passing the House of Lords, was rejected by the Committee in the House of Commons. He was one of the advisers to the Postmaster-General for the acquisition of the telephone system.

Mr. Hammond was well known in the capacity of a writer. In 1883 he published the first book written on private house electric lighting, entitled "Electric Light in our Homes." He also produced numerous Papers and articles for Technical Societies and the Press. One of these Papers, which he read before the British Association in Johannesburg in 1905, was on "Electric Power Distribution for the Rand." In it he advocated the erection of generating works at Vereeniging. This drew strong opposition for some years, but the Victoria Falls and Power Co., which took up the business, eventually followed the lines laid down by him, and erected their works at Vereeniging. In 1884 he founded the Hammond Electrical Engineering College, and in 1890 the Electrical Standardizing, Testing and Training Institution. His death took place at Hampstead, London, on 5th August 1915, in his sixty-sixth year. He was elected a Member of this Institution in 1899. He was also a Member of the Institution of Civil Engineers, of the Institution of Electrical Engineers, and of the Association of Consulting Engineers.

Otto Simon Henry Harcourt, the eldest son of the late G. S. Harcourt, was born at Wraysbury, Bucks, on 25th January 1849. He was educated at Felstead Grammar School, and served for three years, 1865 to 1868, as apprentice to Messrs. J. Simpson and Sons, London, after which he went to Messrs. Beyer and Peacock, Manchester, for one year. He then entered the North London Railway Co.'s Locomotive Works at Bow in 1869, and in the following year went to the Landore Siemens Steel Co., Swansea, where he remained until 1873. On leaving this firm he was engaged by Messrs, Cory Bros., Cardiff,

for a time. He was next appointed, in 1874, engineer to the Laurium Lead Co., at Ergasteria, Greece, and in 1875 went to Messrs. Thomas Hawksley and Son, with whom he remained until 1878. He next became inspecting engineer for Sir A. M. Rendel, St. Paul's Railway Co., the New Zealand Government Engineers, Messrs. Hermans, Faulkiner and Tancred, and others. In 1883 Mr. Harcourt commenced commercial life, and represented Messrs. Brown, Bayley and Dixon, of Sheffield, until 1887; the Bolton Iron and Steel Co., of Lancashire, from 1887 to 1890; Messrs. Taylor Bros. and Co., of Leeds, for eighteen years, and Messrs. Steel, Peech and Tozer, of Sheffield. This firm he represented in Australia for seven years prior to his death, which took place in London on 5th November 1915, in his sixty-seventh year. He was elected a Member of this Institution in 1891.

Edward Palmer Hetherington was born in Carlisle on 6th March 1857. He was educated at Hannah's School, Carlisle. From 1871 to 1877 he served his apprenticeship with Messrs. Lees and Graham, Carlisle, and Messrs. Cowans, Sheldon and Co. of the same city. On leaving the latter firm, he was for three and a half years assistant water inspector to the Gas and Water Department of the Carlisle Corporation, after which he took up a position with Messrs. Hetherington and Co., Manchester, with whom he remained until 1892. He left in that year to join Messrs. W. Muir and Co., Ltd., of Manchester, as their representative, and in 1897 became one of the directors of the firm. In 1899 he returned to Messrs. Hetherington as director, and was holding that post at the time of his death, which took place in Manchester on 24th October 1915, in his fifty-ninth year. He was elected a Member of this Institution in 1897.

Lieutenant Frederick Hollingsworth was born in London on 5th March 1884. He was educated at the Stationers' Company's School, Stroud Green, London, from 1892 to 1899, and then received private tuition for one year, which was followed by a technical course at the Durham College of Science from 1900 to 1901. In 1900 he began

a term of apprenticeship with Messrs. Robert Stephenson and Co., Ltd., Newcastle-on-Tyne and Darlington, and on its completion in 1905 he joined the staff of the London, Brighton and South Coast Railway, at their running sheds at Fratton, Portsmouth, and also attended the Portsmouth Technical School. In 1907 he became technical assistant of the railway department of the Vacuum Oil Co., Ltd., London and in December of the same year he was appointed chief engineer of the South African branch of the company. This position he held until May 1912, when he became assistant district locomotive superintendent of the Beira and Mashonaland and Rhodesia Railways at Umtali, and in the following year was transferred to the position of works manager of the Umtali workshops. In October 1914 he was granted extended leave of absence, to enable him to proceed on active service with the 1st Rhodesian Regiment. Lieutenant Hollingsworth was killed in action at Trekkopjes, German South-West Africa, on 26th April 1915, at the age of thirty-one. He was elected a Graduate of this Institution in 1905, and an Associate Member in 1912.

CARL ALBERT HOLMSTRÖM was born at Horeda, Sweden, on 3rd February 1861. He received his technical education at the Technical College, Norrköping, Sweden, on leaving which he was for two and a half years technical instructor at the Practical School of Engineering, Christinehamn. He came to England in 1886 to enter the drawing office of the Maxim-Nordenfeldt Co., where he brought out in 1889 a semi-automatic gun which had some success. In 1895 he went to China as technical representative of Messrs. Vickers, Sons and Maxim. On his return to England in 1901 he joined Messrs. William Beardmore and Co., of Glasgow, as manager of the ordnance department. In 1905 he entered the firm of Messrs. John Brown and Co., and while there invented a breech mechanism for quick-firing guns. He was still with this firm at the time of his death, which took place at Epsom on 10th September 1915, in his fifty-fifth year. He was elected a Member of this Institution in 1892.

WILLIAM DOUGLASS JAMES was born at Yelverton, Devon, on 23rd September 1892. He was educated at Plymouth College, and in 1909 passed the Intermediate B.Sc. examination in Engineering. In 1910 he started his apprenticeship with Mr. A. E. Douglass, M.Inst.C.E., of the South Staffordshire Water Works Co., and in October 1911 went to Pembroke College, Cambridge, where he took the Engineering side and in 1914 he left, having obtained a second class in the Mechanical Sciences Tripos. He was proceeding as pupil to the Engineer-in-Chief of the Mersey Docks and Harbour Board when war was declared, and he as a member of the O.T.C. was given a commission in the Royal Garrison Artillery as special reserve. He was killed in action in France on 25th September 1915, at the age of twenty-three. He became a Graduate of this Institution in 1911.

HENRY DEAKIN LILEY was born in London on 11th February 1889. He was educated at St. Leonards and at Christ's College, Cambridge. In 1911 he started his pupilage with Messrs. Ruston, Proctor and Co., Ltd., Lincoln, and on its termination he went to the Royal Aircraft Factory, Farnborough, where he carried out valuable investigations in the development of instruments for use on aeroplanes, much of which work has been embodied in actual improvements to aeroplanes at the Front. His death took place at Shoreham on 12th July 1915, at the age of twenty-six, as the result of an aeroplane accident. He became a Graduate of this Institution in 1912.

GEORGE FITZWILLIAM STUART MACLEAN was born at Dunedin, Otago, New Zealand, on 19th August 1865. His early education was obtained locally, after which he served a five years' apprenticeship from 1883 to 1888 with the firm of Kincaid, McQueen & Co. On its completion he remained for two years with the firm as journeyman engine fitter. During this latter period he also attended the Dunedin Technical School for a course of mathematics. In 1890 he became engineer-in-charge of Henry North's barbed wire manufactory, and at the end of the year took up an important

position with the firm of R. S. Sparrow and Co., of Dunedin, being engaged in the work of erecting, launching, and fitting up several gold-mining dredges. From 1892 to 1897 he was employed by the Sew Hoy Big Beach Gold Mining Co., as engineer-in-charge of their dredges, and in the latter year he transferred his services to Messrs. Cossens and Black, of Dunedin, as works manager, with whom he remained until his death, which took place at Dunedin after a long illness, on 7th April 1915, in his fiftieth year. He was elected an Associate Member of this Institution in 1914.

Alfred Richmond Sillar was born at Rhyl, North Wales, on 22nd April 1871. He was educated at Shrewsbury School and received his technical education at the City and Guilds Technical College, Finsbury. He served an apprenticeship of two years, 1888 to 1890, with the Electrical Engineering Corporation, Ltd., of Westminster and Drayton, and in 1891 was engaged by Messrs. J. G. Statter and Co., and afterwards by Messrs. Foote and Milne, their successors, as junior assistant and outside foreman. He finally became contracts manager, and in 1895 took charge of the electrical contracts at the Great Wheel, Earl's Court. In 1896 he was appointed resident engineer to the Blackpool Winter Gardens Co., where he erected what was then the largest private power station in England, and three years later he became Borough Electrical Engineer to Colchester. After holding that post for several years, he took up an appointment as chief electrical engineer and technical adviser of the Peking Chinese Electric Light and Power Co., Ltd. His death took place at Peking on 21st May 1913, at the age of forty-two. He was elected an Associate Member of this Institution in 1905, and was transferred to full Membership in 1908.

Robert Harry Unsworth was born in Manchester on 8th December 1864. He received his education privately, and served his apprenticeship with Messrs. Mather and Platt, Manchester, from 1878 to 1885, in which year he started a course of technical

education at the Royal College of Science, Dublin, leaving in 1887 with a Whitworth Scholarship and the Diploma of Associate. In 1888 he was engaged by Messrs. Ransomes and Rapier, Ltd., of Ipswich, as draughtsman. He was made assistant works manager in 1892 and works manager in 1896, ultimately joining the Board of Directors, and filling the position of general manager. His death took place suddenly at Birmingham on 20th March 1915, at the age of fifty. He was prominently engaged in the designing of the sluices for the Manchester Ship Canal, and for those of the Aswân Dam. He was interested in inventions with regard to the elevating gear for concrete mixers, as well as a special digging crane which could be readily converted into a standard breakdown crane. He took a prominent part in the education of young engineers, and was a member of the Advisory Committee formed for the purpose of assisting the local Education Committee. He was elected a Member of this Institution in 1904.

Colonel Thomas Edward Vickers, C.B., was born in Sheffield on 9th July 1833. He was educated at the Sheffield Collegiate School, and acquired his first technicalities of the industry of iron and steel at Neuwied-on-the-Rhine. On his return to England about 1854, he took charge of the hammers and rolling mills of the Millsands Works. He soon discovered the limitations of this establishment, and centred his thoughts on selecting a fresh site. This was found at Brightside, and developed into the present undertaking known as the River Don Works. In the year that he returned from Germany he acquired a German invention for a moulding composition which could withstand the heat of molten steel. He adopted the process and used it with great success at the Millsands Works. In 1864 he himself invented a double rolling mill for rough-rolling railway tyres from a punched bloom. Such a mill was constructed and erected in 1867 at the River Don Works, and is still running successfully.

In 1870 began the developments in the production of good steel by the open-hearth process. The adoption of his tyre mill and of the open-hearth process, as against the crucible, led to the

remarkable development of the Vickers firm. In 1867 the business was converted into a Limited Company, of which Colonel Vickers became chairman a few years later. The firm gradually acquired the reputation of producing steel of unquestionable quality and reliability. In 1882 guns and armour plates were added to the products of the undertaking, and in 1888 the firm was selected by the Government for the making of armour plates. In the year 1897 the Naval Construction and Armaments Company's Works at Barrow were acquired. Another step towards progress was marked by the purchase of the Maxim-Nordenfeldt Guns and Ammunitions Company. As a result of this, the Company's undertakings were extended to Birmingham and Erith, and other important branches and concessions were developed at home and abroad, the style of the firm being changed to Vickers, Sons, and Maxim, and again changed in 1911 to Vickers Limited. This purchase and the possession of the Barrow yard made it possible for the firm to construct a battleship without any outside help whatever. He retired from the chairmanship of the Company in 1909.

Colonel Vickers was amongst the first to join the Volunteer movement, eventually becoming Colonel of the Hallamshire Rifles. In 1898 he received the distinction of Companion of the Order of the Bath for his services. His death took place in London on 19th October 1915, at the age of eighty-two. He was a Justice of the Peace for the West Riding of Yorkshire and for the City of Sheffield, and was Master Cutler in 1872. He was elected a Member of this Institution in 1861, in which year he read a Paper on "The Strength of Steel containing different proportions of Carbon." He was also a Member of the Institution of Civil Engineers and of the Iron and Steel Institute.

John Drummond Young was born in Glasgow on 27th April 1850. He was educated at the Glasgow High School, and served his apprenticeship with the Port Dundas Pottery Co. from 1866 to 1873, when he became a partner of the firm. In 1881, on the formation of the Scottish Boiler Insurance and Engine Inspection Co., he was appointed managing director, and

was holding this post at the time of his death, which took place in Glasgow on 12th August 1915, in his sixty-sixth year. For almost forty years he served as an officer in the Volunteer Force, retiring in 1905 with the rank of Colonel. He was elected an Associate of this Institution in 1899.

INDEX.

1915.

October–December.

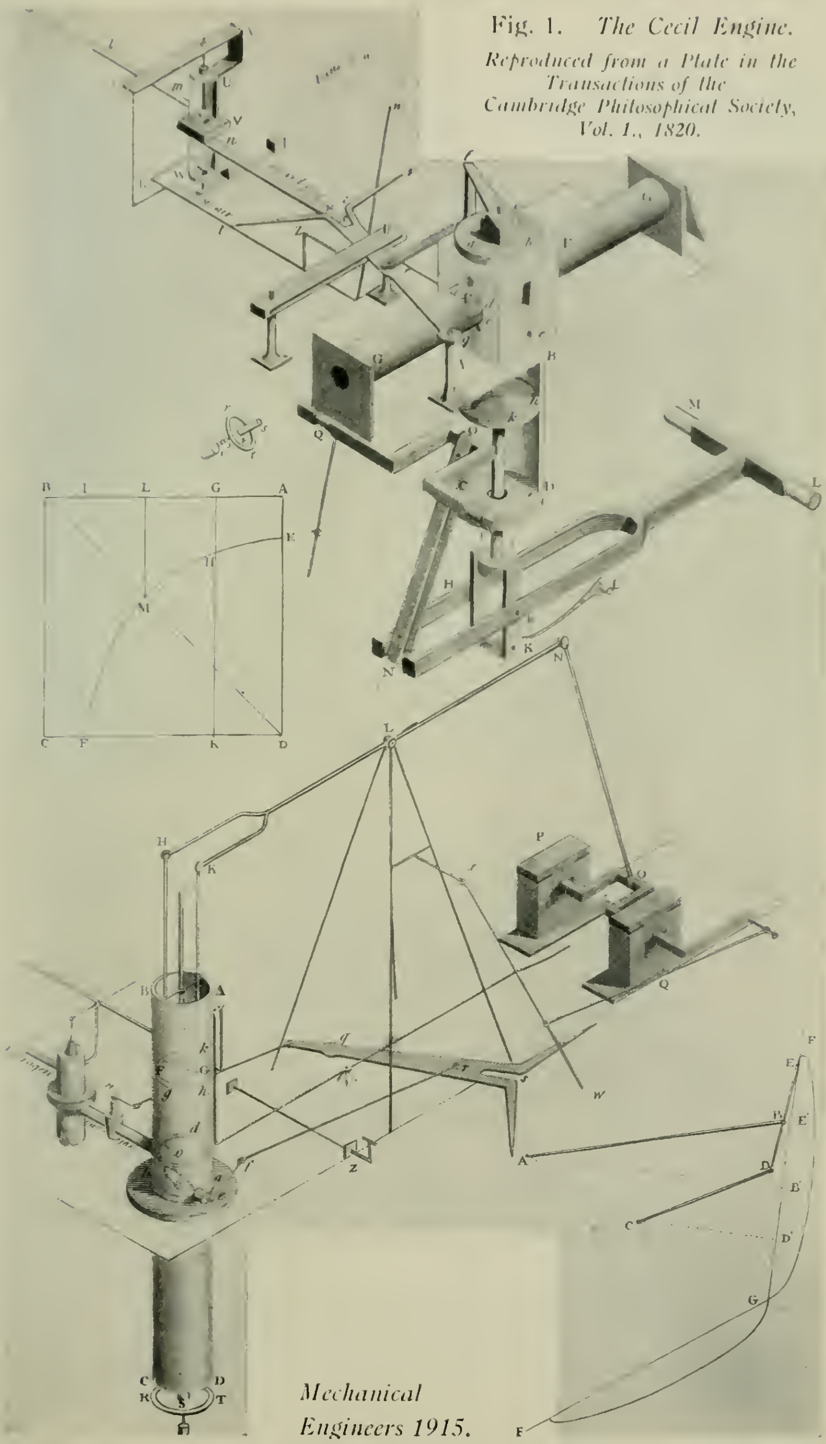

Fig. 1. *The Cecil Engine.*

Reproduced from a Plate in the Transactions of the Cambridge Philosophical Society, Vol. 1., 1820.

Mechanical Engineers 1915.

Fig. 2. ½ *H.P. Lenoir Gas-Engine, 1866.*

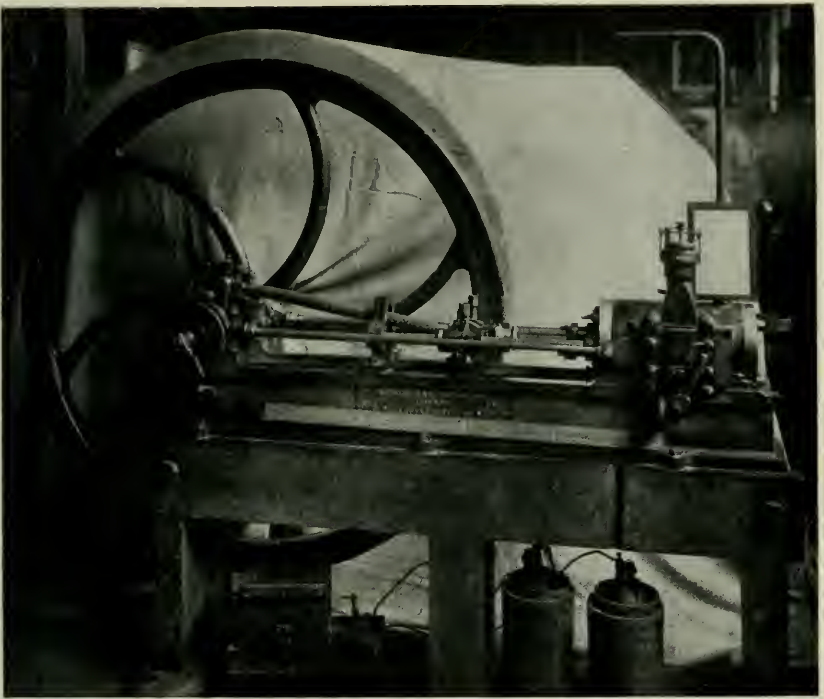

Fig. 3. *Constant-Pressure Engine, Brayton, 1873.*

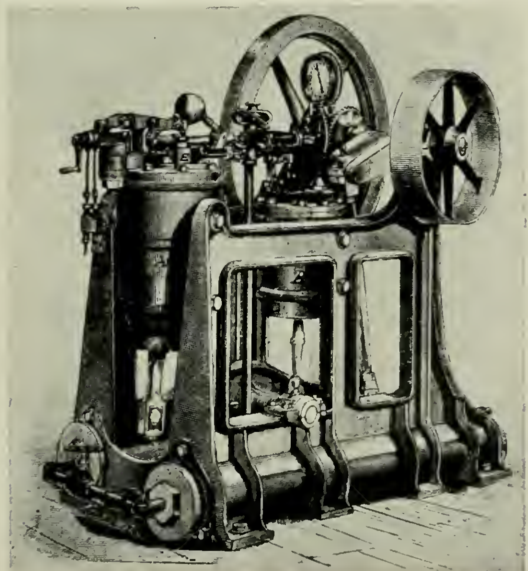

Fig. 3. Annealed. 0·75 Carbon. 4·95 % Molybdenum.
Etched with picric acid. × 400 diameters.

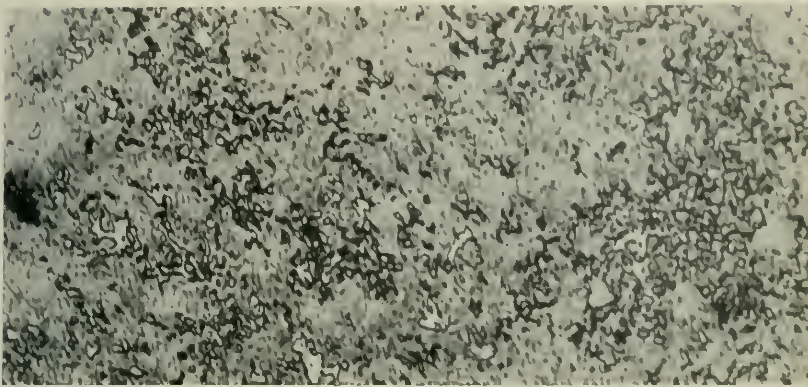

Fig. 4. *0·79 Carbon. 15·46 Molybdenum. × 250 diameters.*
Quenched in water from 990° C. (1,814° F.) Etched with picric acid.
Shows considerable transformation of ferro-molybdenum pearlite into its hardenite.

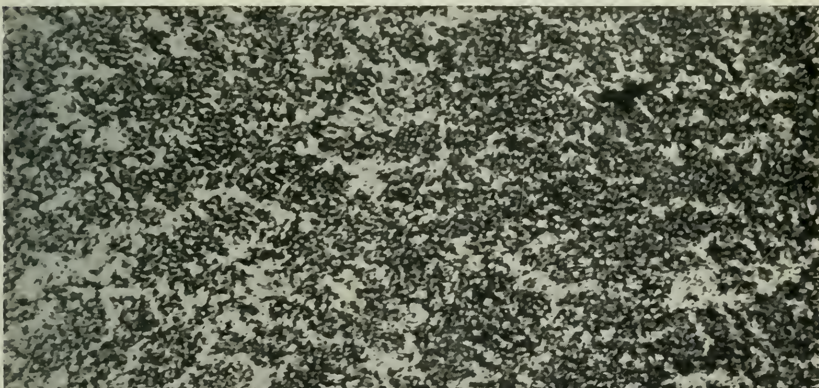

Fig. 5. *Annealed. 0·82% Carbon. 20·70% Molybdenum.*
Etched with sodium picrate. × 250 diameters.

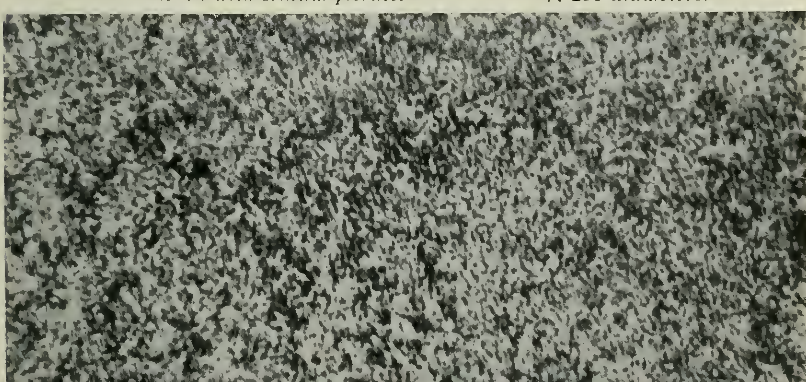

Fig. 3. *Static Torsion Test. Test-Bar, half scale. 6" parallel, 0·8" diam., or 0·5 sq. in area.*

Fig. 5. *Transverse Section of Frozen Ghosts which have protruded into the fluid metal for ⅜" over a length of several inches. Magnified 50 diams.*

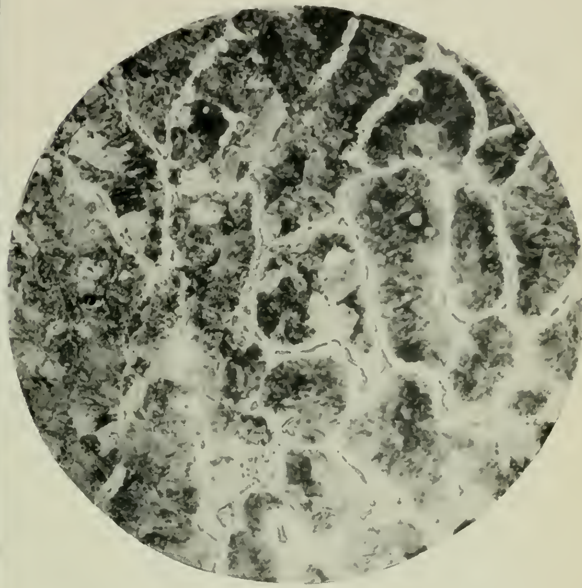

Fig. 6. *Transverse Section of Non-segregated Steel in the vicinity of the Frozen Ghost. Magnified 50 diams.*

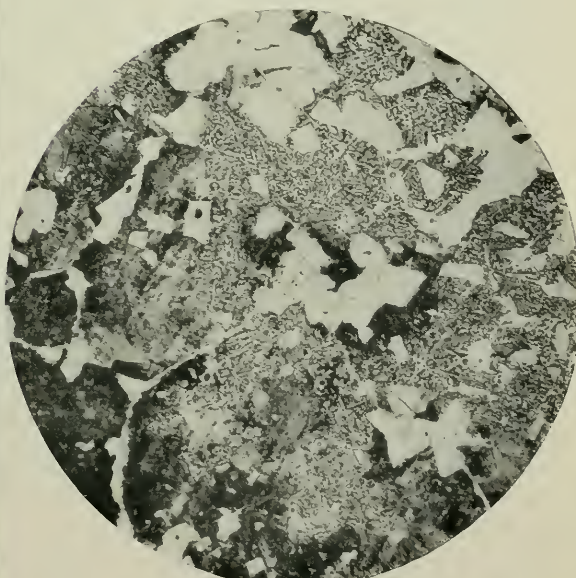

Fig. 7.

Photograph (½ scale) from Large Ingot (Fig 4).

Vertical line indicates apex of one of the octagonal angles in which "Ghost Lines" appear.
Black disk indicates where drillings were taken.

18/4/16.